REPORT

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August 2009

Hydro-Climate Model Selection and Application on the Athabasca and Beaver River Basins

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Attention: Dr. Robert Magai

Re: Hydro-Climate Model Selection and Application on the Athabasca River and Beaver River Basins – Final Report

Dear Dr. Magai:

As per the Terms of Reference in the Request for Proposal AB-2008-03818 for a Hydro-Climate Modeling Study of the Lower Athabasca Regional Plan Area, our Proposal P08CAL0596 dated 27 October, 2008, and the terms of the Agreement No. 09-0257 under which the study was conducted by Golder Associates Ltd., we are pleased to submit this final report on the study. The report, model and data files, and maps are provided electronically on a DVD

Please contact me at (403) 260 2292 should you require any clarification regarding the report.

Yours truly,

GOLDER ASSOCIATES LTD.

Anil Beersing, Ph.D., P.Eng.
Project Manager
Principal, Senior Water Resources Engineer

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Golder Associates Ltd. (Golder) acknowledges the assistance of the following staff of Alberta Environment (AENV) and Alberta Sustainable Resource Development (SRD) to the study:

- Mr. John Kenney (AENV), Project Contracting Manager, who provided overall direction to the study, supplied the relevant information from Albert Environment (AENV), coordinated the inputs and participation from AENV, and provided AENV's review comments on the various draft technical memoranda submitted by Golder Associates Ltd. (Golder) during the study;
- Dr. Robert Magai (AENV), Project Manager during the second phase of the project, who coordinated the review of the draft final report and facilitated the discussion with and inputs of the various AENV team members;
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- Dr. Caroline Bampfylde (AENV); and,
- Dr. John Diiwu, Forest Hydrology Specialist with Alberta Sustainable Resource Development (SRD).

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- Dr. Lei Chen;
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EXECUTIVE SUMMARY

One of the factors affecting future water supply is the nature of the future climate regime. The effects of climate change on water yield from the basins of Alberta will affect water uses and water management in those basins. Alberta is embarking on a regional planning process and the effect of climate change on watershed responses is a key consideration in that process. Hydrologic models have commonly been used to assess the effects of climate change on watershed hydrology. As part of a regionally specific initiative for the Lower Athabasca Regional Plan, Alberta Environment (AENV) has identified the need for a hydrologic model to assist it in assessing the effects of climate change on water yield in the Lower Athabasca Regional Plan Area (LARP), and in the Athabasca River Basin and the Beaver River Basin, in particular. The intent is that the outcome of this regional initiative can be used as a prototype to support similar projects in other regions. Further to a Request for Proposals and the submission of proposal by Golder Associates Ltd. (Golder), AENV contracted Golder Associates Ltd. (Golder) to develop criteria for the selection of an appropriate hydrologic model, to develop an approach to implement the selected model, to apply the selected model to the Athabasca River and Beaver River Basins using five climate change scenarios, and to assess the results of the simulations.

The model selection criteria included considerations of a number of factors including the (1) range and mathematical representation of hydrologic processes in the model and the temporal scale of the simulations, (2) applicability of calibrated model parameters or current simulation modules even under modified climate regimes, (3) flexibility of model to simulate hydrologic processes over a wide range of modeling scale; (4) extent of climate, watershed, vegetation, and soil data requirements for running the model, (5) ability of input data structure of model to support the format of downscaled climate change scenario data; (6) outputs of model and their relevance to support water and watershed management in Alberta; and, (7) currency or peer-acceptance of model. Ten hydrologic models were evaluated for the purposes of this study: WATFLOOD, MISBA, MIKE-SHE, HSPF, HEC-HMS, HYDROTEL, SSARR, DHM-RS, VIC and CHRM.

The three top-ranked models were WATFLOOD, MIKE-SHE and HSPF. MIKE-SHE is ranked first among the three because of its physically-based approaches for simulating hydrologic processes, sophisticated hydraulic routing capabilities, and excellent technical support and documentation. The scores for WATFLOOD and HSPF were not too different from each other. Both MIKE-SHE and WATFLOOD are proprietary softwares with no option for code modification by the user. HSPF is the other model in the top-tier. The representation of hydrologic processes in HSPF is not as sophisticated as those in MIKE-SHE, however, they are still fairly rigorous and are widely acceptable and used. When only selection criteria 1 (*Criteria relevant to objectives of study – hydrologic effects of climate change*) and 3 (*Criteria Determining the Degree of Sophistication of the Processes Simulated in the Model)* are considered, HSPF and WATFLOOD are scored very close to each other, with MIKE-SHE scoring higher than either. When only selection criterion 3 is considered on its own, the three models are ranked as follows: 1: WATFLOOD, 2: HSPF, and 3: MIKE-SHE. HSPF is a public domain model. Since its initial development nearly twenty years ago, the HSPF model has been applied throughout North America and numerous countries and in various climatic regimes around the world. The modules for simulating hydrologic processes within the model (e.g., snowmelt runoff, infiltration, etc.) are reasonably sophisticated for the purposes of this project. Based on the model selection criteria and further evaluations of the top-ranked models and full weighting of considerations for the purposes of this particular project, and discussions with AENV, the HSPF model was selected for implementation on the Athabasca River and Beaver River because of its overall good compromise between sophistication, user-friendly attributes, and wide use. MIKE-SHE and WATFLOOD were the next most appropriate models in order of preference.

The HSPF model was calibrated and validated for application to the Athabasca River Basin and Beaver River Basin. Each basin was sub-divided on the basis of drainage network, locations of gauging stations, and surficial geology. Temperature and precipitation data for the calibration of the model were from climate stations closest (specific selection based on availability of concurrent climate and flow data) to the sub-basins. Seven sub-basins (tributary to the Athabasca River) were selected for calibration of the model. Six nodes located on the main stem of the Athabasca River were selected for validation of the calibrated parameters. The calibration on mean annual and/or mean open-water flows is generally good for most calibration sub-basins. With respect to mean monthly flows, the calibration is generally reasonable, although there are some significant differences

between observed and simulated values for some winter months. The calibrated model reproduced the measured discharges at the validation nodes on the main stem of the Athabasca River well to reasonably well, giving confidence in the use of the model for assessing the hydrologic effects of potential future climate changes. It was concluded that the calibrated HSPF model has been validated and is appropriate for assessing the effects of climate change on the yield in the Lower Athabasca Regional Plan Area.

To address the potential effects of climate change on water yield in the Lower Athabasca Regional Plan Area (LARP), which includes the downstream portion of the Athabasca River Basin and the Beaver River Basin, the HSPF model, calibrated and validated for these two basins, has been used to simulate the hydrologic effects of forecasted future climate scenarios. The 1961 to 1990 period was used as the climatological baseline period for the effects assessments.

As a first step in addressing the potential effects of climate change on key ecosystem variables in Alberta, Alberta Environment has developed a comprehensive database (Alberta Climate Model) of thirteen climate variables from the available Environment Canada's climate records from 1961 to 1990 (Alberta Environment 2005). AENV provided Golder with the Alberta Climate Model data and average monthly changes in temperature and precipitation predicted by five GCMs for two future periods: 2010 to 2039 (referred to as 2020s) and 2040 to 2069 (referred to as 2050s). Average (1961-1990) monthly temperature and precipitation values are available for grids of size of approximately 1 km by 1 km (0.0083333°) covering the entire province. The five climate scenarios (2020s and 2050s) provided by AENV were:

- CCSRNIES_A1F1 (warmer and drier than median conditions);
- CGCM2_B23 (cooler and drier than median conditions);
- HADCM3_A2A (warmer and wetter than median conditions);
- HADCM3_B2B (median conditions); and,
- NCARPPCM_A1B (cooler and wetter than median conditions).

The average (2010-2039 and 2040-2069) monthly temperature and precipitation values are made available for the same grids as the baseline climate for the entire province. The baseline (1961-1990), 2020s and 2050s average monthly temperature and precipitation values for each of the sub-basins included in the HSPF model were estimated as the average of the grid cell values within the sub-basins. The differences between the baseline averages and the 2020s averages, and the differences between the baseline averages and the 2050s averages were then estimated. The average change in mean annual precipitation varies from -1% to +7% for the 2020s scenarios and from +2% to +13% for the 2050s scenarios. The range of the change in precipitation is much wider on a monthly basis: -10% to +23% for the 2020s scenarios and -15% to +46% for the 2050s scenarios. The average increase in mean annual temperature varies from 0.63°C to 1.52°C for the 2020s scenarios and from 1.77°C to 4.35°C for the 2050s scenarios.

The Alberta Climate Model provides only the average (1961-1990) monthly temperature and precipitation values. The HSPF model is a continuous simulation model that requires temperature and precipitation inputs as daily values. Using the same data from which the Alberta Climate Model was derived, daily series of temperature and precipitation were compiled from data at seven index climate stations in the LARP area. The observed data were used with the estimated differences for the 2020s and 2050s to create daily series of future climate scenarios, which were then used with HSPF to develop forecasted flow series for the 2020s and 2050s.

The HSPF model calibrated for the Athabasca River Basin and Beaver River Basin was run with the baseline climate data and the adjusted future climate data. The effects on flows were assessed using the flow statistics at selected locations on the main stem of the Athabasca River and on the Beaver River at the Cold Lake Reserve for the 2020s and 2050s climate scenarios.

General conclusions are as follows:

- All the five climate scenarios for the 2020s tend to result in lower mean annual flows, with the decrease in mean annual flow becoming more severe downstream along the Athabasca River.
- Changes in mean monthly flows for the 2020s scenarios tend to be positive (increase relative to baseline values) during the spring months and significantly negative (decrease) during the summer months. The seasonal differences in flows are consistent with the relative effects of increased precipitation (more spring runoff) and increased temperatures during the summer months (higher summer evapotranspiration).
- The 2050s climate scenarios result in changes in mean annual flow that are generally more severe compared to the 2020s scenarios, which is consistent with the forecasted changes in temperature and precipitation.
- The range of effects of future climate regimes on flows in the Lower Athabasca Regional Plan Area (LARP) is summarized below. Three locations are used for the summary: (1) Athabasca River at Athabasca (07BE001) to represent inflow to the LARP area, (2) Athabasca River below McMurray (07DA001) to represent flows in the oil sands region where the amount of water withdrawal is a key consideration in the planning process, and (3) Beaver River at Cold Lake Reserve sub-basin (06AD006) to represent the southern portion of the LARP area.

  The summary results indicate that water yield from the two basins will generally decrease, with the effects (in percentage terms) more significant during the month of August. The effects on low February flows, although reduced, tend to be less (in percentage terms) compared to changes in August flows. Flood flows tend to be higher under the future climate scenarios.

Range of Potential Future Climate Effects on Flows in the Lower Athabasca Region

Flow Statistic	Athabasca River at Athabasca			Athabasca River at McMurray			Beaver River at Cold Lake		
	Range of Change in Flow (%)			Range of Change in Flow (%)			Range of Change in Flow (%)		
2020s	Low	High	Median	Low	High	Median	Low	High	Median
Mean Annual Flow	-16%	-5%	-9%	-15%	-2%	-6%	-22%	0%	-7%
Mean August Flow	-19%	-11%	-16%	-21%	-6%	-14%	-30%	-2%	-22%
Mean February Flow	-15%	-4%	-7%	-12%	-1%	-4%	-26%	-3%	-10%
Mean June or April Flow	-17%	7%	-4%	-17%	7%	-5%	-4%	11%	3%
10-year Flood Flow	-17%	2%	-7%	-18%	4%	-3%	-22%	17%	10%
2050s	Low	High	Median	Low	High	Median	Low	High	Median
Mean Annual Flow	-21%	-4%	-12%	-21%	-4%	-8%	-19%	-2%	-10%
Mean August Flow	-34%	-10%	-24%	-31%	-12%	-21%	-27%	-15%	-24%
Mean February Flow	-17%	0%	-8%	-13%	1%	-8%	-19%	-7%	-12%
Mean June or April Flow	-12%	2%	-5%	-15%	4%	-3%	-5%	18%	5%
10-year Flood Flow	-11%	-3%	-7%	-15%	-2%	-4%	-11%	24%	-3%

Labels for Climate Scenarios	
CCSRNIES-A1F1	C1
CGCM-B23	C2
HADCM3-A2A	H1
HADCM3-B2B	H2
NCARPCM-A1B	N

The results of the assessment of the effects of climate change on flows in the Athabasca River and Beaver River basins tend to be in general agreement with recent studies carried out by independent researchers. Studies on the effects of potential climate change on flows in watersheds in Alberta include those by Kerhoven and Gan (2005) on the Athabasca River Basin (ARB) and Pietroniro *et al.* (2006) on the South Saskatchewan River Basin (SSRB). Kerkhoven and Gan (2006) predicted that mean annual flows in the ARB would decrease by almost 25% by the last 30 years of the century. Pietroniro and Toth (2006) predict general reduction in flows in the SSRB ranging from -13% to -4%.

The range of effects predicted by the HSPF model for the LARP area is generally consistent with the results of similar studies in Alberta. Depending on the flow statistic, the range of effects can span more than 10%, which reflects the assumptions inherent in the formulation of the climate scenarios as well as uncertainties in the predictions. The range of hydrologic effects predicted by the HSPF model for the LARP area reflects the range of conditions that basin planners should consider. Hence, the predicted effects using HSPF and future climate scenarios provide a rational basis for water management and planning purposes in the LARP area.

The scope of work for this study included an assessment of flow variability relative to effects due to forecasted climate scenarios. Flow series can be dominated by departures from mean conditions at seasonal to multi-decadal time scales. The variability has been linked to sea surface temperature anomalies in the tropical and extra-tropical regions of the Pacific Ocean, ENSO and PDO, respectively. Wet and dry cycles have significant implications for prairie communities and economies and the management of land and water resources. The calibrated HSPF model calibrated for the Athabasca River Basin was used on the Firebag River sub-basin to generate a baseline (1961-1990) as well as a 54-year (1954-2007) series of flows using available data at the Fort McMurray Airport climate station. It was assumed that the simulated 55-year flow data series may capture the variability due to past ENSO events and possibly some past PDO events to a greater extent than the standard 30-year (1961-1990) series. The effect of future climate scenarios on flow variability was assessed by comparing the standard deviation and coefficient of variation for the two (1961-1990 and 1954-2007) annual flow series under the baseline, 2020s and 2050s climate scenarios. The calculated coefficients of variation suggest that there is no difference (difference not statistically significant) between the baseline 1961-1990 and 1954-2007 series, as well between the same two series under the five climate scenarios for the 2020s and 2050s. One reason for the lack of difference between the two series (30-year and 54-year) is likely because the 54-year is still too short and does not include the extreme wet and dry cycles of the past as suggested by analysis of tree-ring records.

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1.0 INTRODUCTION

1.1 Background

The *Alberta Water for Life* Strategy was developed to achieve safe, secure drinking water, healthy aquatic ecosystems, and reliable water supplies of suitable quality for a sustainable economy. The potential gap between water demand and water supply in the future, when water demands are expected to increase and water supplies may decrease, is a key consideration in the *Alberta Water for Life* Strategy. One of the factors affecting future water supply is the nature of the future climate regime. The effects of climate change on water yield from the basins of Alberta will affect water uses and water management in those basins. There is a need to assess the potential effects so that watershed planners can adapt their plans to take advantage of positive effects and implement mitigation measures to minimize the negative effects.

Alberta is embarking on a regional planning process and the effect of climate change on watershed responses is a key consideration in that process. One consideration of this regional process is that there is consistency in how the effects of climate change from the various basins are estimated and assessed. Depending on the hydrologic response to climate change, the effects on water yield from a basin can increase or decrease or there may be shifts in seasonal patterns. Hydrologic models have commonly been used to assess the effects of climate change on watershed hydrology. One approach is to use simulated outputs from GCMs for the next few decades as inputs into hydrologic models to assess the hydrological responses of the basins under future modelled climate regimes. As part of a regionally specific initiative for the Lower Athabasca Regional Plan, Alberta Environment (AENV) has identified the need for a hydrologic model to assist it in assessing the effects of climate change on water yield in the Lower Athabasca Regional Plan area (LARP). The intent is that the outcome of this regional initiative can be used as a prototype to support similar projects in other regions.

Further to a Request for Proposals and the submission of proposal by Golder Associates Ltd. (Golder), Alberta Environment (AENV) contracted Golder to develop criteria for the selection of an appropriate hydrologic model, to develop an approach to implement the selected model, to apply the selected model to the Athabasca River and Beaver River Basins using five climate change scenarios, and to assess the results of the simulations. Phase I of the project consisted of two tasks. The first task was the selection of an appropriate model based on criteria that are flexible enough to be transferable to the various Planning Regions of the province. The follow-up task was to develop a strategy to implement the selected model to the LARP area, and the Athabasca River Basin and the Beaver River Basin, in particular. Phase II of the project consisted of the following tasks: calibration and validation of the selected model on the Athabasca and Beaver River basins; implementation of the calibrated model using baseline (1961-1990) climate data and GCM-forecasted climate data for five climate scenarios for the 2020s and 2050s; and assessment of effects of climate change on flow variability.

This report presents the model selection criteria, the recommended model for implementation, the results of the calibration and validation of the selected model on the Athabasca River Basin and the Beaver River Basin, and the results of the assessment of future climate scenarios on flows in the two basins.

2.0 MODEL SELECTION

2.1 Model Selection Criteria

The model selection criteria can be broadly categorized in terms of (1) range and mathematical representation of hydrologic processes in the model and the temporal scale of the simulations (hours to months), (2) applicability of calibrated model parameters or current simulation modules even under modified climate regimes, (3) flexibility of model to simulate hydrologic processes over a wide range of modeling scale, i.e, from large basins to small tributary basins; (4) extent of climate, watershed, vegetation, and soil data requirements for running the model, including the ability to use remote sensing data, (5) ability of input data structure of model to support the format of downscaled climate change scenario data; (6) outputs of model and their relevance to support Regional Planning efforts under the Land Use Framework and generally to water and watershed management in Alberta; and, (7) currency or peer-acceptance of model. A number of specific criteria and sub-criteria were then developed from these broad considerations.

Table A.1 in Appendix A lists the models and the model selection criteria that were used to select a hydrologic model for hydro-climate modeling in Alberta. The criteria belong to the following general categories:

1. <u>*Criteria relevant to objectives of study – hydrologic effects of climate change*</u>

These include:

a. Ability to incorporate key watershed features (physiographic, hydrographic, geologic, etc.)
b. Ability to simulate hydrologic processes dominant in region or watershed under consideration
c. Ability to simulate hydrologic processes over multi-year periods
d. Ability to simulate hydraulic features (channel, floodplain storage, lake storage, etc.)
e. Ability to produce outputs at spatial scale of interest (grid to watershed scale)
f. Ability to produce outputs at time scale of interest (hourly to annual), including floods, droughts, monthly yield and annual yield
g. Ability of model to use format of downscaled climate data (grid, basin, etc.)

These criteria define the high-level functions of the model that are key to addressing the objective of a study, namely, the assessment of the effects of climate change on water yield. Each criterion is further defined in terms of specific sub-criteria that may be region, climate or specific output dependent. For example, while hydraulic routing is a key criteria, the ability to simulate ice jams or break-up is likely not significant for water yield studies. On the other hand, it could be a significant criterion for assessing the effects of climate change on flood magnitude and timing where floods are governed by such events.

A numerical ranking from 5 (Critical) to 0 (No value) determines the importance of the sub-criteria to the specific study objective being considered. A numerical ranking from 5 (Very Well) to 0 (Not Simulated) describes how well the model meets the sub-criteria. The product of the two scores provides an indication of the ability of the model to address the key study objectives.

2. <u>*Criteria Defining Data Requirements of Model*</u>

These include:

h. Climate
i. Watershed
j. Stream
k. Geology
l. Vegetation

These criteria determine whether the spatial and temporal resolution of the data required by the model matches that of the available data. A numerical ranking from 5 (Available) to 0 (Not Available) specifies the resolution of the data available, while the actual data resolution required by the model is specified in terms of 1 (Yes) and

0 (No). The product of the two scores provides an indication of whether the data requirements of the model match what are available.

3. *Criteria Determining the Degree of Sophistication of the Processes Simulated in the Model*

These include:

m. Rainfall-Runoff
n. Snowmelt-Runoff
o. Evaporation/Evapotranspiration
p. Routing in Streams
q. Infiltration
r. Glacier melt

While criteria 1.a to 1.g define the process that are key the study objectives, criteria 3.m to 3.r define the method used to simulate the processes. The method may range from the simple to the very complex, and one model may have options for the user to select between several of the methods. A numerical ranking from 5 (Critical) to 0 (No value) determines the importance of the various approaches to the specific study objective being considered. The degree of sophistication in the approach that is important to the study objective may be dependent on the region where the model is being applied. While sophisticated snowmelt routines would be required in areas where snowmelt is the major source of water supply, the same degree of sophistication may not be necessary in areas where snowmelt is a minor contributor to runoff. A numerical ranking from 5 (Very Well) to 0 (Not Simulated) describes how well the model meets the sub-criteria. The product of the two scores provides an indication of the ability of the model to address the key study objectives using approaches or methods that are deemed to be necessary for useful model outputs.

4. *Criteria Defining Ease of Use by Modeler*

These include:

s. Model availability
t. Training/Support
u. Operating System
v. Model Description
w. Modification of Model by User

These criteria determine whether there is adequate documentation on the model and whether the model is useable in the modeller's work environment. A numerical ranking from 5 (Critical) to 0 (No value) determines the importance of the various requirements to the user. The ability of the model to meet these requirements is specified in terms of 1 (yes) and 0 (no). The product of the two scores provides an indication of whether the user documentation requirements match the model specifications.

The next three set of criteria define the ability of the model to address key user requirements during the model implementation stage, such as model calibration, model data management and assessment of uncertainty in model outputs. These criteria are:

5. *Criteria for Model Calibration and Validation*

These criteria determine whether the model has in-built modules or can output simulation results that facilitate the assessment of calibration or validation performance. Sub-criteria include graphics modules to display observed and simulated stream flow series, generate statistics of observed and simulated series, and for automatic optimization of calibration parameters based on the model performance statistics.

6. *Criteria for Data Management*

These criteria determine whether the model has user-friendly input and output data management systems. Sub-criteria include ability of model to import input data from standard spreadsheets such as Excel and/or from GIS files or remotely sensed data files. The ability to the model to format the simulation results for output to similar

data formats is also a sub-criterion. The internal data management capabilities of the model can also be a key user requirement.

7. *Criteria for Uncertainty Analysis*

These criteria determine whether the model has the capability for uncertainty analysis on simulation results, such as, generation of random values of calibrated parameters from user-specified probability distributions of expected deviations of calibration parameters from their expected calibrated values or ability to accept multiple synthetically-generated input data series.

A numerical ranking from 5 (Critical) to 0 (No value) determines the importance of the various requirements to the user. The ability of the model to meet these requirements is specified in terms of 1 (yes) and 0 (no). The product of the two scores provides an indication of whether the model meets these requirements.

The sum of all the scores for each model is used as an indication of the appropriateness of the various candidate models to meet the objectives of the study, to have the necessary data to run, as well as to meet user requirements.

2.2 Models under Consideration

Tables A.2 to A.11 in Appendix A describe the assessments of the ten hydrologic models that were evaluated for the purposes of this study: WATFLOOD, MISBA, MIKE-SHE, HSPF, HEC-HMS, HYDROTEL, SSARR, DHM-RS, VIC and CHRM.

2.2.1 Conceptualizing Hydrologic Processes in a Hydrologic Model

A hydrologic model transforms input, I(t), to output, Q(t), via a set of equations or transfer function, f, such that

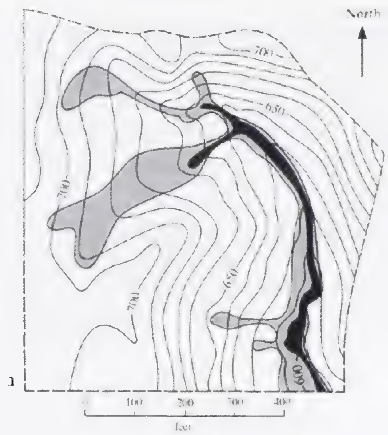
$$Q(t) = f[I(t)] \qquad (1)$$

The solution of Equation (1) uses the basic principles of conservation of mass, momentum, and energy, but does not generally account for the precise flow pattern inside a control volume. Given that the Rainfall-Runoff (r-r) relationship is highly nonlinear, Equation (1) would be too complex to characterize all the components of the rainfall-runoff transformation process. Therefore, in modeling r-r, modeling concepts (model parameters) are introduced to disaggregate and simplify the complex process to concepts that are manageable, for example:

(1) Threshold Concept of Infiltration

Surface Runoff $r=(i-f)$ *if* $(i-f)>0$ where i = rainfall intensity and f = rate of infiltration which is function of soil moisture.

(2) Variable Source/Contributing area Concept


Dunne and Leopold (1978, Fig. 9-11)

The % of basin area contributing to runoff during the course of a storm varies with time. As the water table approaches the surface, the contributing area increases and vice versa, e.g., coupled effects of surface cover and soil moisture (see diagram of Dunne and Leopold, 1978).

2.2.2 Modeling Scales and Approaches

Mathematical models are constructed at some preferred scales for conceptual analysis, for verification by observations, and for predictive purposes. Outputs from the same models, but executed at different spatial scales, can be somewhat different because assumptions made at one scale may contradict the assumptions made at another scale. Spatial scales appropriate for hydrologic models are generally of the order of 10 – 100 km, with time scales generally one day. In contrast, for atmospheric models like the General Circulation Models (GCMs) used for forecasting future climate regimes, spatial scales are typically 100's km, and time scales are minutes to hours. One common approach to reconcile the different scales of most hydrologic models and the GCMs is to parameterize those processes at the micro-scale (sub-basin) that affect water behaviour at the meso-scale (large watersheds or regions) as hydrologic concepts at micro-scale are well established, but not so at mesoscale. Another approach is to disaggregate the macro-scale concept to allow for processes and for parameter variations at the meso-scale of interest, but there are few such attempts, e.g., Schaake's disaggregation model from, annual to monthly time step.

2.2.3 Brief Descriptions of Models

Some models are more based on parameterization, others on physically-based processes, depending on the types and resolution of data available to drive the model. The former models are less data intensive than the latter models, but they also tend to depend more on parameter calibrations. The models (Tables A.2 to A.11 in Appendix A), described briefly below, represent quite a wide range of hydrologic models developed in the last several decades.

WATFLOOD

WATFLOOD was developed by Kouwen (1998) of the University of Waterloo. As a fully distributed model, WATFLOOD models a watershed in terms of grouped response units (GRUs), and is also designed to use gridded data sources such as land cover, DEM's, numerical weather prediction model output, and radar data. Since it uses GRUs and land cover data, it is possible to use "universal parameters" with some fine tuning or calibration. The model, written in separate programming units, runs at hourly time steps and can simulate up to

100 storm events. It divides a watershed into a surface upper zone (saturated, varying depth), an unsaturated zone, and a saturated lower zone. Hydrologic processes considered are evaporation loss using Hargreaves, or Priestley-Taylor algorithms, soil infiltration by Green-Ampt's model, Hortonian runoff, Eric Anderson's snow model (temperature index) with cover based snow cover depletion curves, Hartly's sediment model and a crude glacier melt model. For routing, it uses a center difference, kinematic wave routing scheme with variable time steps to satisfy the Courant criteria. WATFLOOD has been used with grid sizes ranging from 1 to 25 km and for watershed areas from 15 to 1,700,000 km^2.

MISBA

MISBA is a fully distributed, soil–vegetation–atmosphere transfer model (SVAT) that considers interactions between the soil–biosphere–atmosphere (ISBA) of Me´te´o France (Noilhan and Planton, 1989), and modified and applied to the Athabasca River Basin (ARB) to model its water and energy fluxes by Kerkhoven and Gan (2006). It models the energy and water processes at the land surface directly on the basis of eight parameters at time steps in seconds: soil clay content, soil sand content, fraction of land covered by surface water, depth of soil column, heat capacity of vegetation, and three stomatal resistance parameters. Its input data includes ERA-40 historical re-analysis dataset developed by the European Centre for Mid-range Weather Forecasts (ECMWF), DEM data, landuse types, initial soil moisture, initial soil ice content, initial deep soil temperature, surface albedo, leaf area index, vegetative cover fraction, vegetative roughness length, and radiative fluxes. It considers the sub-grid heterogeneity of the moisture capacity of the soil to follow the Xinanjiang distribution.

MIKE-SHE

MIKE-SHE, developed by Abbott *et al.* (1986), offers several different approaches for hydrologic simulation, ranging from simple, lumped and conceptual approaches to advanced, distributed and physically-based approaches. It considers precipitation (rain or snow), evapotranspiration, including canopy interception, overland sheet flow, channel flow, unsaturated sub-surface flow, and saturated groundwater flow. If the unsaturated zone is considered, MIKE-SHE will calculate infiltration, actual evapotranspiration and recharge; otherwise, groundwater recharge must be specified. The unsaturated zone is a vertical soil profile model that interacts with both the overland flow and the groundwater model. Infiltration can be computed using, either, a simple 2-layer root-zone mass balance approach, a gravity flow model, or a full Richard's equation model, all of which require specification of certain soil-properties. MIKE-SHE comes with a database of various soils and typical crops for different climatic regions of the world, either through pseudo-transfer functions that link suction, water content and hydraulic conductivity, or soil properties specified directly. Groundwater flow is computed using a 2D or 3D finite-difference groundwater model similar to MODFLOW. The river flow component is a dynamic, 1-D modeling tool, ranging from a simple Muskingum routing to the higher order dynamic wave formulation of the Saint-Venant equations, while the overland-flow component includes a 2D finite difference diffusive wave approach using the same 2D mesh as the groundwater component. The overland flow module is designed to interact with the river, the unsaturated zone, and saturated groundwater zone.

HSPF

HSPF uses a version of the Stanford Watershed Model (Crawford and Linsley, 1966), which is a deterministic, lumped, conceptual hydrologic model and so it has modest data requirements. It distributes the incoming rainfall into canopy interception, impervious areas, upper zone which will appear as surface runoff or interflow, and infiltration into the lower zone storage divided into active and inactive groundwater storages. The three conceptual storages regulate soil moisture and groundwater storages, while evapotranspiration can extract moisture from the interception, upper, lower and groundwater storages. Runoff from the channel inflow is routed by a hydrologic routing technique that accounts for attenuation by the storage effect of the channel.

HEC-HMS

HEC-HMS is a new version of HEC-1 developed by the US Army Corps of Engineers' Hydrologic Engineering Center (HEC, 1998). Over the years, it has undergone many versions. It is also a soil-moisture accounting model. The latest version includes synthetic unit hydrograph by Snyder's method, instantaneous unit

hydrograph by Clark's method, SCS curve number, exponential decay function, Holtan's equation and TR-20 to compute infiltration loss, streamflow routing, Green-Ampt infiltration equation, degree-day snowmelt modeling, Muskingum-Cunge flood routing, subarea runoff computation, hydrograph combining. Parameters calibration can be done using the univariate gradient method, and Nelder and Mead Simplex method.

HYDROTEL

HYDROTEL, developed by Fortin *et al.* (1986), is a spatially distributed hydrological model based on physical processes specifically developed to facilitate the use of remote sensing and geographical information system data. Various processes are written in modules to allow users having a choice of algorithms with respect to the data available to drive the model, even allowing addition of new algorithms or modules. The model can run at various time steps from one to 24 hours, and it consists of the following components: meteorological data, accumulation and melt of the snow cover, potential evapotranspiration, vertical water budget, surface and sub-surface runoff, and river routing.

SSARR

Developed in 1966 by US Army Corps of Engineers, the SSARR model has been used in many locations around the world including North America, Central and South America, Europe, Southeast Asia, and the Indian peninsula under a variety of climatic conditions and basin sizes ranging from 5 to over 400,000 km^2. The SSARR model is a computerised watershed model plus a river and reservoir system model. It was developed to provide hydraulic simulations for system analyses for planning, design, and operation of water control works and for operational river forecasting. The model combines basin runoff techniques producing surface and subsurface flow with river and reservoir routing techniques. Special optional routines include snow accumulation and snowmelt, soil moisture, recommended for calibration. Daily data from multiple stations include observed precipitation and streamflow, plus forecasted precipitation, and maximum air temperature. Snow conditions, soil moisture, solar radiation forecast, etc. can either be input or allowed to be computed as functions of other parameters. Printed output can include all input data plus forecasted information including surface and subsurface flow, percentage runoff, snow water equivalent, snowline elevation, soil moisture, river stages and discharges, and reservoir inflows, outflows and storage volumes.

DPHM-RS

DPHM-RS was developed by Biftu and Gan (2001, 2004) for the semi-arid climate of the Canadian Prairies. The model can adequately account for a river basin's terrain features by sub-dividing it into sub-basins of uneven shapes and sizes (semi-distributed) based on topographic information derived from the digital terrain elevation (DTED) data. It is computationally modest, designed to effectively assimilate remotely sensed (RS) data, and has most of its parameters determined through RS data and measurements. The hydrologic processes are estimated for each land cover and then aggregated according to the percentage of each land cover present within each sub-basin. Evapotranspiration (ET) from each land cover is estimated at three levels by the two-source model that separately considers evaporation from soil and plants. The soil moisture at the top active and the transmission zones are estimated by a water budget approach, while the groundwater dynamics by the topographic soil index obtained from DTED. The surface runoff from each sub-basin is routed to the channel network by a kinematic wave response function, and then routed to the basin outlet by the Muskingum-Cunge model.

VIC

VIC-3L is a three-layer Variable Infiltration Capacity (VIC-3L). It is a hydrologically based land surface model that is classified under the surface vegetation atmospheric transfer scheme (SVATS). VIC-3L considers both energy and water balances, and represents explicitly the effects of multiple vegetation covers on water and energy budgets. Input data are such as vegetation covers, soil classifications, and forcing data such as precipitation and air temperature data. VIC-3L also incorporates the representation of sub-grid spatial variability of precipitation with the representation of spatial variability of infiltration to simulate energy and water budgets (e.g., energy fluxes, runoff and soil moisture). It includes both the saturation and infiltration excess runoff

processes in a model grid cell with consideration of the subgrid-scale soil heterogeneity, and the frozen soil processes for cold climate conditions. Liang and Xie (2001) improved VIC-3L's (Liang et al., 1996) runoff predictions by developing a runoff parameterization scheme incorporating both Dunne and Horton runoff mechanisms.

CRHM

CHRM model is a physically-based model primarily developed by the University of Saskatchewan for cold region applications and muskeg hydrology in northern Saskatchewan. Using physically-based algorithms, CRHM considers blowing snow transport by wind, snow interception, sublimation, snowmelt, infiltration into frozen soils, hillslope water movement over permafrost, actual evaporation, and radiation exchange to complex surfaces, overland flow, organic layer subsurface flow, mineral interflow, groundwater flow, and streamflow. CRHM has no provision for calibration; parameters and model structure are selected based on the understanding of the hydrological system. It models a watershed using the concept of Hydrologic Response Unit (HRU). More information about CRHM is given in Pomeroy et al. (2007).

2.3 Selected Model

Table A.1 in Appendix A shows each model's total score. The detailed evaluation of each model against the selection criteria are provided in Tables A.2 to A.11 Appendix A. The model rankings, based on their total scores and suitability for this project, can be categorized as follows:

Top tier:	MIKE-SHE, HSPF, WATFLOOD
Middle tier:	DPHM-RS, VIC, CRHM
Bottom tier:	HYDROTEL, SSARR, MISBA, HEC-HMS

DPHM-RS, VIC and CRHM are sophisticated, currently research-oriented, hydrologic models with modules that tend to simulate hydrologic processes using sophisticated and accepted physically-based formulations. Ideally, such models have the potential to provide scientifically very defensible results on the effects of climate change on water yield. However, these models are still under development with few or limited real-world applications and uncertain technical support. These models may still have "bugs" or errors since they are yet to be tested in wide usage. These models will require significant effort and interaction with the model developers over a long period of time to implement province-wide or for multiple large watersheds. Hence, despite their inherent strengths as physically-based models (hence, their relatively high scores), they are not recommended for this project's particular application. Nevertheless, a comparison between VIC and the recommended model (HSPF) is presented below to highlight each other's strengths and weaknesses. The information can be useful for a future study where the constraints of a research model are of lesser importance.

The bottom-tier models (HYDROTEL, SSARR, MISBA, HEC-HMS) are commercial or public-domain models that have been applied in real-world applications, with some of the applications reported in either the grey- or peer-reviewed literature, and have reasonable levels of technical support. However, these models are not deemed to be appropriate for this project's particular application for the following reasons. MISBA, a grid-based model, is best suited for large watersheds and, once set up for such watersheds, can be difficult to extract runoff characteristics at the sub-basin level because of the lack of a channel routing component. There is limited real-world applications of HYDROTEL reported in the literature, with virtually no technical support. In addition, the model codes and descriptions of the codes tend to be mostly in French, hence, limiting its present application within Alberta Environment with few francophone modellers. SSARR is a conceptual precipitation-runoff model that is very good at flood forecasting and reservoir routing simulations, however, its hydrologic formulations may not be sophisticated enough to capture the effects of climate change on water yield. The snow melt routine in HEC-HMS is based on the relatively simple degree-day approach. The soil water balance and groundwater simulation modules are also based on relatively simple algorithms that may not adequately capture the spatial variability of yield in large watersheds with varied soil characteristics. The simple routines may not be sophisticated enough to capture the effects of climate change on the magnitude and/or timing of snow melt runoff, which is a key component of the yield from the Athabasca River basin. Hence, these models

(HYDROTEL, SSARR, MISBA, HEC-HMS) are not recommended unless models in the top-tier and middle-tier cannot be implemented.

The three top-ranked models are WATFLOOD, MIKE-SHE and HSPF. MIKE-SHE is ranked first among the three because of its physically-based approaches for simulating hydrologic processes, sophisticated hydraulic routing capabilities, and excellent technical support and documentation. The scores for WATFLOOD and HSPF are not too different from each other. WATFLOOD is in the top-tier for similar reasons as MIKE-SHE, however, WATFLOOD is not yet as widely used as MIKE-SHE and is still a DOS-based software. Both MIKE-SHE and WATFLOOD are proprietary softwares with no option for code modification by the user. HSPF is the other model in the top-tier. The representation of hydrologic processes in HSPF is not as sophisticated as those in MIKE-SHE, however, they are still fairly rigorous and are widely acceptable and used. HSPF is a public domain model. When only selection criteria 1 (*Criteria relevant to objectives of study – hydrologic effects of climate change*) and 3 (*Criteria Determining the Degree of Sophistication of the Processes Simulated in the Model)* are considered, HSPF and WATFLOOD are scored very close to each other, with MIKE-SHE scoring higher than either. When only selection criterion 3 is considered on its own, the three models are ranked as follows: 1: WATFLOOD, 2: HSPF, and 3: MIKE-SHE.

Based on the model selection criteria and evaluations presented in Tables 1 and 2, full weighting of considerations for the purposes of this particular project, discussions with AENV and on the discussion presented below, it is recommended that the HSPF model, although last in the top-tier, be implemented for the Athabasca River and Beaver River basins in north-east Alberta because of its overall good compromise between sophistication, user-friendly attributes, and wide use. MIKE-SHE and WATFLOOD are the next most appropriate models in order of preference. These two models are compared below. A comparison of VIC with HSPF is also provided below to assist AENV if it wishes to consider a research model for a future study or a pilot/demonstration study.

The rationale for recommending HSPF as the model for this project is as follows:

Rationale for HSPF Recommendation

Since its initial development nearly twenty years ago, the HSPF model has been applied throughout North America and numerous countries and in various climatic regimes around the world. The modules for simulating hydrologic processes within the model (e.g., snowmelt runoff, infiltration, etc.) are reasonably sophisticated for the purposes of this project. Based on the numerous world-wide practical applications, a database of HSPF calibration parameter values have been compiled through the joint sponsorship of both the U.S. Environmental Protection Agency and the U.S. Geological Survey as reference for practitioners. The availability of reference calibration parameters significantly improves the efficiency (i.e., reduces time requirement) of model calibration and validation. In addition, reference to the experience and results of other applications increases the defensibility of the outputs from HSPF.

Experience with sophisticated models indicates that much of the effort associated with hydrologic implementation is spent on data acquisition and management. Hence, it is essential that a successful comprehensive model include a sound data management component. The HSPF model software is based on a comprehensive data management system operating on direct access. The HSPF simulation modules draw required input data from time series stored in its data management system and are capable of writing output to it. Because these data transfers require very few instructions from the user, the effort required with setting up this hydrologic model for large and complex watersheds is minimized. In addition, the HSPF model includes the following tools which are not necessarily available as a package in other hydrologic model software:

- Source code, executable version, user's guide, and technical support;
- A windows-based and independent interactive interface that is fully integrated with a software product, GenScn, that provides the ability to change an HSPF input sequence interactively, run the model, and analyze results graphically; and,

- WDMUtil, a tool used to manage and create the watershed data management files (WDMs) that contain the meteorological data and other time series data used by HSPF.

Under the sponsorship of U.S. EPA and USGS, HSPF continues to undergo refinement and enhancement of its component simulation capabilities, along with user support and code maintenance activities.

One drawback of the HSPF model for application with gridded climate data is that HSPF is implemented at a sub-basin level, that is, it is not based on grid cells as other comparable models are. This implies that the gridded climate scenario data will require aggregation at the sub-basin level, which will require some effort on the part of the user and potentially loss of input data details. In addition, aggregation may reduce some of the spatial variability in the climate data. This is important if the spatial variability of climate parameters is expected to change under projected climate change scenarios. However, this potential drawback can be mitigated to some extent by subdividing the watershed into sub-basins that are reasonably small that spatially variability is less of an issue. The user should be careful not to sub-divide more than necessary because routing of the runoff from a large number of sub-basins without detailed hydraulic information can be another source of uncertainty.

MIKE-SHE compared to WATFLOOD

MIKE-SHE and WATFLOOD operate at a grid level, which enhances the ability to import gridded climate scenario data. Both models have good modules for simulating key hydrologic processes. Both models can use data from remote sensing and GIS as inputs. However, MIKE-SHE has the advantage of including both simple and advanced hydrologic process descriptions that can operate at either a grid-scale or a sub-watershed scale. Hence, the user can choose the hydrologic module component that more appropriately makes effective use of the available data, achieves the purpose of the hydrologic modelling exercise and provides the required end results to maximize computational efficiency. This choice is not available in WATFLOOD since it operates at a grid level only and has limited choices for hydrologic and hydraulic simulations. In addition, MIKE-SHE can be easily linked to other regional and local scale models such as MIKE 11 for flood routing, MIKE-WQ for simulation of water quality, and FEFLOW for groundwater simulation. It includes a complete user interface, sophisticated input and output tools, including animations, compared to WATFLOOD that operates in a DOS environment and provides only text output. The drawback of MIKE-SHE is the significant amount of effort required to compile the extensive data required to run the model. MIKE-SHE is also a very sophisticated model with a steep learning curve. It requires considerable time to become familiar with and to be implemented by a novice user.

HSPF compared to VIC

The following is a summary comparison between VIC and HSPF:

- Spatial Scale: VIC is macro scale model that operates at grid scale with typical scale of application of 1/8 to 2 degrees latitude by longitude (minimum grid size ~ 10 km). The HSPF model operates at sub-basin scale.
- Spatial distribution of surficial soil type: The VIC model assumes one surficial soil type for each grid. For the HSPF model, the modeller can sub-divide the sub-basin to account for various soil types.
- Spatial variability in soil moisture holding capacity: The VIC model accounts for spatial variability of soil moisture holding capacity at the grid level, while the HSPF model accounts for spatial variation of infiltration at sub-basin level.
- Base flow: The VIC model simulates baseflow using a non-linear model. HSPF simulates groundwater flow using a linear or non-linear model.
- Runoff: The VIC model has two runoff components (Surface and Baseflow) while HSPF model accounts for three runoff components (Surface, Interflow and Baseflow).

- Snow transport and sublimation: In 2004 the snow transport and sublimation model component developed John Pomeroy and his team was incorporated within the VIC model for application on two watersheds in Alaska and NWT. The HSPF model does not have a component to simulate these phenomena.

- Snow distribution: VIC can take the effect of snow distribution with elevation band in the grid for snow melt simulation. HSPF has only one parameter for updating land covered by snow at each simulation time step.

- Snow Melt Runoff algorithm: VIC uses a complete energy balance at the canopy and ground levels to simulate snow melt runoff. HSPF model uses both the temperature index and energy balance methods. However, the energy balance method includes some empirical equations for simulation of sensible, latent and long-wave radiation.

- Effect of frozen soils: VIC includes a detailed method to account for frozen soil conditions and for permafrost. HSPF uses a conceptual parameter to account for frozen conditions in winter.

- Flow Routing: VIC model uses "separate and independent" routing models for routing flows from grid to grid and through the channel systems. The overland routing is based on a "Unit Hydrograph" approach and this needs to be developed at the implementation stage and provided as input. Channel routing is based on the linearized Saint-Venant Equation. The HSPF model's overland flow routing is based on Manning's Equation, while channel routing is based on storage routing.

- Overall Model Comparison: HSPF has the advantage in terms of practical application for more than 20 years, having central data base management, easy to set-up and has GUI for pre- and post-processing, Windows-based application and detailed user manuals and documents. The VIC model has several sub-modules that a user needs to be familiar with and compile individually to generate the executable code, requires significant pre-processing of input data with no central data management systems and a significant level of effort for the two separate routing models.

Summary of Model Selection Task

HSPF is considered to be a practical model with good technical support and sufficient scientific rigour in its representation of hydrologic processes to address the requirements of this project. It is recommended for this project.

The MIKE-SHE and WATFLOOD models are good alternative models, however, based on the full weighing of considerations, options and suitability for the tasks for this particular project, HSPF was selected in the final consultations. VIC is a sophisticated research model that AENV may consider for a future study or a pilot study.

AENV gave Golder its approval to proceed with the implementation of the HSPF model on the Athabasca and Beaver watersheds for the climate change modeling. AENV noted that it has some concerns with the approach that HSPF uses to simulate the snowmelt process. AENV requested that Golder provides it with the details and results of the calibration and validation of HSPF as soon as that is completed so that treatment of snowmelt can be discussed. During the next phase of the project, Golder confirmed with AENV that the energy method was being used in the implementation of the HSPF model to the Athabasca River Basin and the Beaver River Basin.

3.0 MODEL IMPLEMENTATION STRATEGY

3.1 Implementation Approach

Following the model selection task, the next step in Phase I of the project was the development of a strategy for implementing the selected model on the Athabasca and Beaver River Basins (henceforth generically referred to as "basin"). The approach should be flexible enough to accommodate the possibility of adjustments that may be required for implementing a different model selected for another region.

Essential elements of the implementation approach include:

- Compile available model input data for the basin, including data on climate, soil, vegetation, etc., for calibration and validation purposes.
- Compile flow data from gauged watersheds for calibration and validation purposes.
- Assess changes in land use patterns in gauged watersheds during the period of available climate and flow data.
- Select one period (5 to 10 years) of climate and flow data that is relatively free of trends and without land use changes for calibration purposes and another similar period (5 to 10 years) for validation purposes. The calibration and validation periods should ideally include both hydrologically wet and dry years.
- Discretize basin into sub-basins or grids (depending on model selected) that are physiographically different, have different geologic characteristics, experience different climate regimes, and have flow data at convenient locations (outlet of sub-basin or aggregation of grids).
- Select climate stations whose data would be representative of the climatic regime within each gauged watershed selected for calibration and validation purposes.
- Calibrate model for each gauged watershed within each hydrologic region encompassed by the basin (the term hydrologic region is explained further below) using statistics such as annual yield, monthly yield, winter flows and flood flows. Compare observed and simulated hydrographs visually.
- Validate model for each gauged watershed within each hydrologic region using input from selected period and comparing observed and simulated data for the same period. Adjust calibration parameters if necessary.
- Use model calibration parameters for each gauged watershed to represent model parameters for each sub-basin encompassing the gauged watershed(s) used for calibration purposes.
- Run the model for the entire basin using available climate data at climate stations in the basin and compare with flows recorded at several hydrometric stations on the main stem of the river. There are several such stations on the Athabasca from Jasper to Fort McMurray.
- If the selected model uses sub-basins for simulation and routing, the baseline (1961-1990) climate data may require aggregation for each sub-basin represented in the model schematic. If the selected model works on a grid basis, then the discretisation of each sub-basin should consider the grid size of the climate data coverage.
- Run the model for the entire basin using the baseline (1961-1990) climate data for the basin and compare with flows recorded at several hydrometric stations on the main stem of the river over the same time period (i.e., 1961-1990). Summarize key hydrologic variables (annual and monthly water yield particularly) at these locations and compare with those using the climate station data.

- AENV will provide five future climate scenarios derived from GCMs using statistical downscaling techniques with the Alberta Climate Model (which represents baseline conditions) for two future 30-year time snapshots. Run the selected and calibrated hydrologic model on the Athabasca River and Beaver River Basins with the five climate change scenarios.

- Summarize key hydrologic variables (annual and monthly water yield particularly) at selected locations within the main stem of the river in the basin. Compare with those from using the baseline Alberta Climate Model data.

3.2 Detailed Implementation Approach

3.2.1 Compilation and Processing of Data

The selected model will require baseline climate, physiography and hydrology data for several sub-basins within the basin for calibration and validation. The first task in implementing the selected model involves the collection and analysis of the relevant data required for the set-up of the model. The information would ideally be compiled within a GIS framework to store the data efficiently, present the information visually, and assist in interpreting the results of the modeling analysis.

Basin Topographic, Soil, Vegetation Data -

- Create a base GIS layer of the basin from digital topographic and stream network maps.

- Sub-divide the basin into a number of sub-basins. Large tributary sub-basins will be further sub-divided to reflect the topographic and climatic variability within such sub-basins. At a minimum, each sub-basin should have at least one gauged watershed in each hydrologic region encompassed by the basin. For the Athabasca River Basin, the Clearwater River Sub-basin will be represented as a single sub-basin, its size notwithstanding, because no hydrologic region has been defined for the portion of the sub-basin lying in Saskatchewan.

  <u>Hydrologic Regions</u>

  As part of the hydrologic regionalization work completed for AENV by Golder in 2006, the Province of Alberta was classified into hydrologic regions. The regionalization was based on topography, climate, hydrology, drainage, geology, and soils. The delineation of the hydrologic regions was determined by comparing the spatial patterns in physiography, geology and climate with the regions and on the basis of hydrologic responses. The analysis of the hydrologic response patterns and physiographic-geologic-climatic spatial patterns resulted in 20 hydrologic regions for the province that represent a reasonable accounting of the various factors influencing the hydrologic response of a watershed. For example, there are seven hydrologic regions, from mountains to foothills to prairies, encompassing the Athabasca River Basin up to Lake Athabasca. See Figure 1 in Appendix 9 of Alberta Water Supply Assessment Report prepared by Golder for AENV in 2007. The figure is reproduced as Figure C.1 in Appendix C of this report.

- Carry out an initial visual analysis using GIS of the spatial variability of the baseline (1961-1990) climate data.

- Overlay the baseline climate data on the base basin GIS layer to identify regions where significant spatial climate variability is evident. It is expected that such spatial variability will already have been captured by using the basin's hydrologic regions. However, if further refinement is required, then the sub-basins will be further sub-divided to reflect the spatial variability in climate.

- IT IS ASSUMED THAT A SUB-BASIN LAYER HAS BEEN CREATED AT THIS STAGE.

- Use the digital elevation model data to develop elevation bands or ground slope maps for each sub-basin. The information is used for delineating recharge/discharge areas, adjusting climate data, routing modules, etc., depending on the hydrologic model being implemented.

- Create a GIS layer of the basin's surficial geology and overlay on sub-basin layer to obtain soil characteristics for each sub-basin. The information is used for specifying infiltration rates, soil moisture capacity, etc., depending on the hydrologic model being implemented.

- Create a GIS layer of the basin's vegetation cover and overlay on sub-basin layer to obtain vegetation characteristics for each sub-basin. The information is used for specifying interception capacity, estimation of evapotranspiration, etc., depending on the hydrologic model being implemented.

Climate Data – A number of climate monitoring stations are in operation in the basin. They include real-time and daily recording stations operated by Environment Canada, and seasonal stations operated by AENV to support forest-fire protection activities. A daily time series of each climate variable required by the selected model should be developed for each station located within or close to gauged watersheds that could potentially be used in the calibration or validation of the selected model.

Hydrometric Data – Water Survey of Canada (WSC) has operated or continues to operate streamflow (hydrometric) monitoring stations on a number of streams within the basin. The gauged watersheds cover a range of drainage areas, elevations, slopes, vegetation characteristics, etc. The data series are not concurrent, but there is good overlap of data series from the 1970s to date. Time series of available data on land use changes and other developments can be compared to periods of flow data to identify the time periods that can be used for the calibration and validation of the selected model.

Land Use Changes – Areas within the basin may have over time undergone changes due to natural resource management activities (agriculture, logging, diversion, etc.) and infrastructure developments (roads, culverts, bridges). For the purpose of this study, an overview of temporal changes in land use/cover in the sub-basins selected for calibration and validation would be conducted to identify sub-basins that are in essentially natural conditions.

Water Level in Lesser Slave Lake – Lesser Slave Lake is a significant waterbody in the Athabasca River basin and Lesser Slave River is a major tributary to the Athabasca River. Water levels for Lesser Slave Lake (LSL) are available from 1979 onwards. AENV has developed a "naturalized" series of flow and water level data, from 1916 to 1999, for a location at the outlet of LSL. The naturalization was based on the calibration and implementation of a SSARR model for the catchment area upstream of the lake outlet. AENV also developed a corresponding series of regulated flows and water levels from 1916 to 1999, based on the known characteristics of the weir. This is a synthetic series, assuming the presence of a weir since 1916. AENV has concluded that the lake water level data corresponding to the post-weir recorded and synthetic regulated series are "very nearly coincident" and that the difference between simulated regulated levels and observed levels since weir construction is "not significant". The hydraulic characteristics of the weir on LSL should be incorporated in the selected model to account for any effects of climate change on water levels in the lake and the consequent effects on flows into the Athabasca River.

River Cross-Section Data – The hydraulic modelling domain is expected to include Lesser Slave Lake, the reach of the Lesser Slave River from the LSL's outlet to the confluence with Athabasca River, Athabasca River downstream of Fort McMurray and up to, but excluding, Lake Athabasca, and the reaches of other major contributing tributaries, contingent on the availability of cross-section data. Cross-sectional data can be obtained from the rating curves developed by WSC at its gauging stations.

3.2.2 Calibration and Validation of Model

- Select at least one gauged watershed with adequate flow records within each hydrologic region of the basin. Select the climate station(s) to represent each hydrologic region. Adjust temperature and precipitation data for elevation if the climate station is at an elevation significantly different from most of the sub-basin.

  If the model uses sub-basins as simulation units, the calibration and validation of the model can proceed for each selected gauged watershed.

If the model uses grids as simulation units, discretize each sub-basin selected for calibration and validation purposes into grid cells based on homogeneity in current land use or cover; ground slope or elevation; soil groups; channel slope; etc. The digital elevation, soil, land use, and hydrography data for the basin will be used for the discretization. The extent of discretization or size of the grid cells will be a balance between a fine level of detail that makes full use of the physically based equations within the selected model and a coarser resolution that recognizes the limitations in data availability. The discretization will take into account land use changes over time. Good representation of the landscape should be achieved without excessive discretization. The compromise between discretization detail and data resolution implies that the model will require calibration. Model parameters will be adjusted based on model simulations and observed flow or water level data at gauged locations.

- Channel routing of runoff will be based on cross-section data, if they are available, or map-derived characteristics (e.g. slope) or area-based estimates (i.e. channel width and depth) or generic values, if they are not available.
- Select two time periods (5 to 10 years each) for which climate, hydrology, and land use data are available from gauged watersheds under natural conditions (i.e. no developments).
- Run the selected model (continuous simulation) using one of the time periods to calibrate the model (continuous simulation) and the other to validate the model. Adjust model parameters until calibration and validation are deemed reasonable based on objective statistical criteria.
- Alternatively, select one gauged sub-basin with a given hydrologic region for calibration and another nearby gauged sub-basin for validation. The climate data series used for calibration and validation do not need to be similar in this approach.
- The model calibration parameters for each gauged watershed can be used for all sub-basins (gauged and ungauged) in the basin, which are similar in topographic, climatic, soil and vegetation characteristics.

3.2.3 Running Climate Scenarios with Calibrated Model

The implementation steps following calibration and validation of the model are as listed above and repeated hereunder:

- Run the model for the entire basin using available climate data at climate stations in the basin and compare with flows recorded at several hydrometric stations on the main stem of the river. There are several such stations on the Athabasca River from Jasper to Fort McMurray.
- If the selected model uses sub-basins for simulation and routing, the baseline (1961-1990) climate data may require aggregation for each sub-basin represented in the model schematic. If the selected model works on a grid basis, then the discretization of each sub-basin should consider the grid size of the climate data coverage.
- Run the model for the entire basin using the baseline (1961-1990) climate data for the basin and compare with flows recorded at several hydrometric stations on the main stem of the river over the same time period (i.e., 1961-1990). Summarize key hydrologic variables (annual and monthly water yield particularly) at these locations and compare with those using the climate station data.
- AENV will provide five future climate scenarios derived from GCMs using statistical downscaling techniques with the Alberta Climate Model (which represents baseline conditions) for two future 30-year time snapshots. Run the selected and calibrated hydrologic model on the Athabasca River and Beaver River Basins with the five climate change scenarios.
- Summarize key hydrologic variables (annual and monthly water yield particularly) at selected locations within the main stem of the river in the basin. Compare with those from using the baseline Alberta Climate Model data.

4.0 CALIBRATION OF HSPF MODEL FOR THE LOWER ATHABASCA REGIONAL PLAN AREA

4.1 Introduction

The HSPF model was selected to assess the hydrologic responses of the Athabasca River Basin and the Beaver River Basin (comprising the Lower Athabasca Regional Plan Area) under future modelled climate regimes forecasted by several Global Climate Models (GCMs) for the next few decades. This section describes the calibration and validation of the HSPF model for the two basins.

4.2 Athabasca River and Beaver River Basins

The Athabasca River starts in the Rocky Mountains near Mount Columbia (elevation 3,747 metres) and flows northeast for 1,400 kilometres until it empties into Lake Athabasca (elevation 208 metres) (http://scienceoutreach.ab.ca/athabasca_region.htm. Accessed 20 June 2009.). Flows from the basin eventually make their way to the Arctic Ocean. The river drains an area of approximately 138,000 km². The river flows past the urban centres of Jasper, Hinton, Whitecourt, Athabasca and Fort McMurray prior to emptying into Lake Athabasca. The Athabasca River Basin includes the McLeod, Pembina and Clearwater rivers.

As a major river system, the Athabasca River is influenced by a variety of climate, terrain and landscape characteristics found within its basin (http://www.ramp-alberta.org/river.aspx. Accessed 20 June 2009.). The seasonality of climatic conditions is a major influence affecting river flow conditions. The climate includes cold winters, when most of the seasonal precipitation falls as snow. Cold winters are typically followed by warm summers, when snow and glacial melt waters from the river's headwaters combine with runoff from localized snowmelt and rainfall events throughout the basin. As the river flows toward Lake Athabasca, water is contributed to the river from individual sub-basins.

The Athabasca River Basin encompasses the following ecoregions (natural regions):

- Rocky Mountain (Alpine, Subalpine, Montain);
- Boreal Foothills;
- Boreal Mixed Wood (dry and wet);
- Boreal Uplands;
- Boreal Lowlands; and,
- Canadian Shield (Athabasca Plains).

The Alberta portion of the Beaver River Basin is located in the east-central part of the province, near the town of Bonnyville. This basin lies entirely within the Boreal Mixedwood Ecoregion (University of Alberta 2005). The Beaver River starts near the town of Lac La Biche as the outflow from Beaver Lake. The basin is characterized by undulating to moderately rolling topography, elevations ranging from about 500 m to 750 m above sea level (AENV 2006) and an abundance of lakes. A significant portion of the low lying areas of the Beaver River Basin is classified as non-contributing because these areas do not contribute stream flows during a storm with a return period less than or equal to 10-year. The Sand River is the largest tributary to the Beaver River.

4.2.1 HSPF Model Setup for the Athabasca River Basin and Beaver River Basin

The continuous (dynamic) Hydrologic Simulation Program Fortran (HSPF) model developed by the U.S. Environmental Protection Agency (U.S. EPA) was selected for the Athabasca River and Beaver River hydro-climate modeling Study. The HSPF model simulates stream flows as the sum of three components: surface flow, interflow and groundwater. The relative magnitude of each component depends on land use, soils and vegetation cover. The model user can specify specific parameters for various land use types to represent the physical processes in a basin.

4.2.1.1 Characteristics of the Athabasca River Basin and Beaver River Basin

The surficial geology of a basin is a significant factor in the hydrologic response of the basin. HSPF models the response of a basin to precipitation based on the soil characteristics (infiltration rate, storage capacity, interflow, etc.) of the various land types in the basin. In the calibration of the HSPF model for the Athabasca River Basin and Beaver River Basin, the discretization of the sub-basins into land types was based on surficial geology. The surficial geology characteristics considered in the set-up of the HSPF model for the Athabasca River Basin and Beaver River Basin are shown in Figure B.1 in Appendix B. The land types in the basin were based on the following nine major surficial geology classifications:

- Well Drained Sand and Rapidly Drained Sand;
- Well Drained Till and Rapidly Drained Till;
- Well Drained Clay Loam;
- Organic Soil;
- Poorly Drained Sand (Lowland Glaciolacustrine);
- Poorly Drained Till (Lowland Glaciofluvial);
- Poorly Drained Clay Loam (Lowland Glacial);
- Impervious/Fractured Rock; and,
- Impervious/Glacier.

The headwaters of the Athabasca River Basin are covered by glaciers. Glaciated areas were modelled as an impervious land type, but with discharges from the glaciated areas when temperatures rise above $0^{o}C$. A significant portion of the upper areas of the Athabasca River Basin is also classified as impervious. However, most of these areas are fractured, thus increasing the travel time of runoff compared to strictly impervious areas. Such areas were treated as “pervious” in the HSPF model, but with appropriate adjustments of the pervious land type parameters.

The characteristics of the vegetation cover in a basin also play a significant role in the basin’s hydrologic response through interception of precipitation, evapotranspiration of intercepted precipitation and water stored in the soil layer, shading of solar radiation (which affects snow melt rate), etc. The vegetation characteristics in the Athabasca River Basin and Beaver River Basin are shown in Figure B.2 provided in Appendix B. The sub-basins in the Athabasca River Basin and Beaver River Basin were not explicitly divided into vegetation types (as was done for land types based on surficial geology), however, the characteristics were considered in the specification of parameters controlling interception, evapotranspiration and shading. A sub-division of land types based on vegetation can be considered for future applications of the model when the effects of changes in vegetation as a result of climate change need to be modelled can be predicted and the hydrologic effects need to be assessed.

4.2.1.2 Representation of Basins in the HSPF Model

The Athabasca River Basin was sub-divided into 75 sub-basins, based on the drainage network and the locations of the WSC stations on gauged sub-basins selected for calibration and validation of the model. The 75 sub-basins were further sub-divided based on surficial geology. The locations of the hydrometric stations for the selected gauged sub-basins are shown in Figure C.2 in Appendix C. The connectivity between the sub-basins and the characteristics of each sub-basin were represented or conceptualized as shown in the schematic of the HSPF model (Figure D.1) in Appendix D. The schematic shows the “HSPF model flow diagram”, which is basically the sequence in which the sub-basins are simulated by HSPF and the connectivity of each sub-basin to downstream receiving reach.

Similarly, the Beaver River Basin was sub-divided into three sub-basins as shown in Figure C.2 in Appendix C.

4.2.1.3 Model Data Input

Data used to run the model were as follows:

- Temperature and precipitation data for the calibration of the model were from climate stations closest (specific selection based on availability of concurrent climate and flow data) to the gauged sub-basins. See Figure C-3 in Appendix C. To account for the spatial variability of precipitation, precipitation data from different stations were assigned to the different Hydrologic Regions encompassed by the Athabasca-Beaver River Basins. The Hydrologic Regions of Alberta were developed by Golder (2006) as part of a project for AENV. See Figure C.1 in Appendix C for the hydrologic regions of the Lower Athabasca Regional Plan Area. The Hydrologic Regions represent areas within which the climate, geology and hydrologic responses are more or less homogeneous, but different from the adjacent Hydrologic Region. The Hydrologic Regions provide a rational basis for assigning climate stations to the sub-basins of the Athabasca River Basin and Beaver River Basin. Table 4.1 shows the climate stations selected for precipitation and temperature data for the sub-basins within the Hydrologic Regions encompassing the Athabasca and Beaver River Basins.

Table 4.1 Climate Stations Selected for Sub-Basins within Hydrologic Regions of Athabasca and Beaver River Basins

Hydrologic Region (HR)	Climate Station(s) Selected for Precipitation and Temperature Data for Sub-Basins within HR	Climate Station(s) Selected for Wind Speed and Dew Point Temperature Data for Sub-Basins within HR
3	Jasper & Jasper Warden	Edson
4	Jasper East Gate	Edson
10.1 (south of Athabasca River)	Edson	Edson
10.2 (north of Athabasca River)	Slave Lake	Edmonton International A. for Wind Speed Edson for Dew Point Temperature
8	Campsite	Edmonton International A.
2C	Lac La Biche	Fort McMurray
9A	Fort McMurray	Fort McMurray
2D	Cold Lake	Edmonton International A.

- Wind speed and dew point temperature data were from the Edmonton International Airport station or Edson depending on the Hydrologic Region as shown in Table 4.1, while solar radiation data were from the Edmonton Stony Plain station. The solar radiation data at the Edmonton Stony Plain Station were assumed to be representative of the entire Athabasca-Beaver River basins because solar radiation tends to be generally less spatially variable than most other climatic variables.

- Evapotranspiration and lake evaporation data were derived using the Morton Model, with air temperature, dew point temperature, precipitation and solar radiation used as input data.

- Channel cross-sections used in generating depth-area-volume-flow tables were estimated from data used by WSC to develop rating curves at the hydrometric gauging stations.

- Recorded stream flows at several hydrometric stations in the basin were used for model calibration and validation.

4.2.1.4 HSPF Model Calibration and Validation

The approach to calibrate the HSPF model was modified slightly from that presented in Section 3.2.2. Instead of calibrating and validating the model using gauged sub-basins within each Hydrologic Region, gauged sub-basins that are dominated by one surficial geology type were selected and the model parameters for this surficial geology type "fixed". The process was repeated for the other surficial geology types. The purpose of this approach was to establish "regional model parameters" that can be transferred to other sub-basins in the region that have similar surficial geology. The effects of land cover or vegetation types were indirectly considered in the modelling through calibration of the parameters that simulate their influences. The vegetation types were considered through the following HSPF model parameters: FOREST (fraction of the pervious land segment that is covered by forest), CEPSC (interception storage capacity), and LZETP (lower zone evapotranspiration parameter). Table 4.2 shows the sub-basins used for calibration and validation, as well as location, drainage area, land type and other information on the sub-basins.

Table 4.2 Characteristics of Sub-Basins Used for Model Calibration and Validation

Hydrologic Region	Station Number	Sub-Basin Name	Calibration or Validation	Latitude (degminsec)	Longitude (degminsec)	Gross Drainage Area (km2)	Percent Land Type	Percent of Hydrologic Region Contributing to Station	Record Length	On Main Stem ?	Calibration/Validation Period Start Year	End Year
3	07AA002	ATHABASCA RIVER NEAR JASPER	Validation	525436	1180325	3,880	26% Well Drained Till, 54% Impervious, 20% Glacier	3-100%	1913 - 2006	Yes	1971	2005
	07AA001	MIETTE RIVER NEAR JASPER	Calibration	525150	1180621	629	31% Well Drained Till, 49% Impervious, 20% Glacier	3-100%	1914 - 2006	No	1995	2006
	07AA007	SUNWAPTA RIVER AT ATHABASCA GLACIER	Calibration	521258	1171355	29	100% Glacier	3-100%	1948 - 2008	No	1994	1996
4	07AD002	ATHABASCA RIVER AT HINTON	Validation	532523	1173414	9,780	26% Well Drained Till,2% Well Drained Sand,64% Impervious,8% Glacier	3-70%, 4-30%	1961 - 2006	Yes	1962	2005
	07BA003	LOVETT RIVER NEAR THE MOUTH	Calibration	525950	1163920	103	100% Well and Rapidly Drained Till	4-100%	1975 - 2007	No	1982	1991
5	07AE001	ATHABASCA RIVER NEAR WINDFALL	Validation	541225	1160345	19,600	49% Well Drained Till,6% Well Drained Sand,1% Poorly Drained Sand,37% Impervious,7% Glacier	3-38%, 4-26%, 5-36%	1960 - 2006	Yes	1962	2005
	07AF907	ERITH RIVER BELOW HANLAN CREEK	Calibration	531408	1163355	595	60% Well Drained Till, 40% Well Drained Clay Loam				1984	1990
2D	06AD006	BEAVER RIVER AT COLD LAKE RESERVE	Validation	542115	1101300	14 500	Calibrated separately (see text for details)	2D-100%	1955 - 2006	Yes	1968	1987
8	07BE001	ATHABASCA RIVER AT ATHABASCA	Validation	544320	1131710	74,600	62% Well Drained Till 12% Well Drained Sand,5% Well Drained Loam,3% Poorly Drained Sand,1% Poorly Drained Loam,10% Impervious,2% Glacier,5% Organic	10-23,8-29,5-17,4-9,3-9,2E-8,2C-4	1913 - 2006	Yes	1962	2005
	07BK007	DRIFTWOOD RIVER NEAR THE MOUTH	Calibration	551519	1141354	2,100	56% Well Drained Till,41% Well Drained Sand,3% Organic	8-100%	1968 - 2006	No	1987	1998
9A	07DA001	ATHABASCA RIVER BELOW MCMURRAY	Validation	564650	1112400	133,000	43% Well Drained Till,8% Well Drained Sand,3% Well Drained Loam,1% Poorly Drained Till,2% Poorly Drained Sand,1% Poorly Drained Loam,6% Impervious,1% Glacier,13% Organic,23% from Clearwater basin	8-45,10-20,5-15,4-4,3-4,2E-3,2C-4,9A-5	1957 - 2006	Yes	1961	2007
	07CD001	CLEARWATER RIVER AT DRAPER	N/A	564107	1111515	30,800	Calibrated separately (see text for details)	8-10, 9A-90 + SK Province	1930 - 2006	No	1961	2007
	07DC001	FIREBAG RIVER NEAR THE MOUTH	N/A	573903	1111205	5,990	22% Lowland Glaciofluvia,78% Upland Glaciofluvia. Used for variability assessment	9A + SK Province	1971 - 2006	No	1975	1986
	07DB005	MACKAY RIVER ABOVE DUNKIRK RIVER	Calibration	564535	1123650	1,010	100% Organic		1983 - 1991	No	1983	1990

At least three years of meteorological and hydrologic data were used to calibrate the HSPF model. Calibration began with an initial estimate of the model parameters based the lower and upper limits of each model parameter as described in the HSPF manual. Then, the simulated monthly and annual runoff volumes were compared to the observed volumes at hydrologic gauging stations. Appropriate parameters were adjusted until the simulated monthly and annual volumes were acceptably close to the observed values. The outcome of the calibration and validation of the HSPF model was deemed to be good to reasonable to poor based on the statistical criteria given in Section 4.2.1.5. Individual event volumes were then calibrated.

Once streamflow volumes were calibrated, flow hydrographs were calibrated using both interflow and channel routing parameters. The shapes of event hydrographs, and to some extent the peak flows, were calibrated by changing the interflow parameters and the appropriate stage-storage-discharge relationships. A combination of manual and automatic (using PEST) calibration were used to derive the model's calibration parameters. The calibration parameters for each of the nine land types are shown in Table 4.3. Values in parentheses in Table 4.3 identify instances when slight changes were made in the parameters of similar land types but located in different parts of the basin.

The specific model calibration approach for the Athabasca-Beaver River Basins is summarized as follows:

- Model parameters for the Well/Rapidly Drained Till land type were calibrated using the recorded stream flows at Lovett River near the Mouth (Environment Canada Hydrometric Station 07BA003). The entire Lovett River sub-basin is covered with the Well/Rapidly Drained Till land type (see Figure 4.1). The precipitation data used were from the Lovett Lookout station and missing winter precipitation data were filled using data from the Edson climate station.

- Model parameters for the Well Drained Clay Loam land type were calibrated using the recorded stream flows at Erith River below Hanlan Creek (Environment Canada Hydrometric Station 07AF907). The surficial geology of the Erith River sub-basin is approximately 60% Well/Rapidly Drained Till and 40% Well Drained Clay Loam (see Figure 4.1). During the calibration process, the model parameters for the Well/Rapidly Drained Till land type as determined during the calibration on the Lovett River sub-basin were transferred to the Erith River sub-basin. The precipitation data used were from the Lovett Lookout station and missing winter precipitation data were filled using data from the Edson climate station.

- Model parameters for the Organic land type were calibrated using the recorded stream flows at Mackay River above Dunkirk River (Environment Canada Hydrometric Station 07DB005). The entire Mackay River above Dunkirk River watershed was assumed to be covered by the Organic land type (see Figure 4.2). The precipitation data used were from Livock Lookout station and the missing winter precipitation data were filled using data from the Fort McMurray Airport climate station.

- Model parameters for the Glacier land type were calibrated using the recorded stream flows at Sunwapta River at Athabasca Glacier (Environment Canada Hydrometric Station 07AA007). The entire Sunwapta River sub-basin was assumed to be covered by glaciers (see Figure 4.1). The precipitation data used were from Jasper & Jasper Warden climate stations.

- Model parameters for the Impervious/Fractured Rock land type were calibrated using the recorded stream flows at Miette River near Jasper (Environment Canada Hydrometric Station 07AA001). The surficial geology of the Miette River sub-basin is approximately 31% Well/Rapidly Drained Till, 20% Glacier, and 49% Impervious/Fractured Rock (see Figure 4.1). During the calibration process, the model parameters for the Well/Rapidly Drained Till and Glacier land types were transferred from those obtained during the calibration of the Lovett River and Sunwapta River sub-basins, respectively. The precipitation data used were from Jasper & Jasper Warden climate stations.

Table 4.3 Calibrated HSPF Model Parameters for the Athabasca and Beaver River Basins

Table 4.3a HSPF Model Parameters (Water) - PLAND

Water Parameter	Meaning	Units	WELL DRAINED TILL	WELL DRAINED SAND	WELL DRAINED CLAY LOAM	POORLY DRAINED TILL (LOWLAND GLACIOFLUVIAL)	POORLY DRAINED SAND (LOWLAND GLACIOLACUSTRINE)	POORLY DRAINED CLAY LOAM (LOWLAND GLACIAL)	ORGANIC	IMPERVIOUS (FRACTURED ROCK TREATED AS PERVIOUS)
FOREST	The fraction of the pervious land segment which is covered by forest	none	0.8	0.5	0.8	0.8	0.8	0.8	0.8	0.2
LZSN	The lower zone nominal storage	in	0.3	2	3.3	0.05	0.3	0.4	0.9	13.26
INFILT	An index to the infiltration capacity of the soil	in/hr	0.008	0.5	0.0173	0.05	0.008	0.01	0.5	0.02 (0.04)
KVARY	parameter which affects the behavior of groundwater recession flow, enabling it to be non-exponential in its decay with time	1/in	0.03	5	1.18	0	0	0	2.847	0.8
AGWRC	The basic groundwater recession rate if KVARY is zero and there is no inflow to groundwater.	1/day	0.993 (0.983)	0.8	0.938	0.87	0.87	0.87	0.992	0.997
PETMAX	The air temperature below which E-T will arbitrarily be reduced below the value obtained from the input time series.	degF	40	40	40	40	40	40	40	40
PETMIN	The temperature below which E-T will be zero regardless of the value in the input time series.	degF	35	35	35	35	35	35	35	35
INFEXP	Exponent in the infiltration equation	none	2	2	2	2	2	2	2	2
INFILD	Ratio between the maximum and mean infiltration capacities	none	2	2	2	2	2	2	2	2
DEEPFR	Fraction of groundwater inflow which will enter deep (inactive) groundwater	none	0	0	0	0.11	0	0	0	0
BASETP	Fraction of remaining potential E-T which can be satisfied from baseflow (groundwater outflow), if enough is available.	none	0.005	0.005	0.005	0.3	0.2	0.2	0.005	0.005
AGWETP	Fraction of remaining potential E-T which can be satisfied from active groundwater storage if enough is available.	none	0.01	0.01	0.01	0.4	0.01	0.01	0.01	0.01
CEPSC	Interception storage capacity.	in	see monthly table	see monthly table	see monthly table	see monthly table	0.1	0.10	see monthly table	see monthly table
UZSN	Upper zone nominal storage.	in	0.1 (0.2)	0.05	0.3	0.5	0.5	0.5	0.703	0.6
NSUR	Manning's n for the overland flow plane.	complex	0.25	0.25	0.25	0.35	0.35	0.35	0.25	0.25
INTFW	Interflow inflow parameter.	none	3.3	4.83	1	25	8	10	8.42	3.3
IRC	Interflow recession parameter	1/day	0.94	0.798	0.534	0.92	0.925	0.925	0.944	0.2
LZETP	Lower zone E-T parameter.	none	see monthly table	see monthly table	see monthly table	see monthly table	0.5	0.5	see monthly table	see monthly table

Interception Monthly Table

	WELL DRAINED TILL	WELL DRAINED SAND	WELL DRAINED CLAY LOAM	POORLY DRAINED TILL (LOWLAND GLACIOFLUVIAL)	POORLY DRAINED SAND (LOWLAND GLACIOLACUSTRINE)	POORLY DRAINED CLAY LOAM (LOWLAND GLACIAL)	ORGANIC	IMPERVIOUS (FRACTURED ROCK TREATED AS PERVIOUS)
Jan	0.5	0.5	0.5	1	N/A	N/A	1	1
Feb	0.5	0.5	0.5	1	N/A	N/A	1	1
Mar	0.1	0.1	0.1	1.2	N/A	N/A	1.2	1.2
Apr	0.1	0.1	0.1	0.4	N/A	N/A	0.4	0.4
May	0.05	0.05	0.05	0.05	N/A	N/A	0.05	0.05
Jun	0.1	0.1	0.1	0.1	N/A	N/A	0.1	0.1
Jul	0.05	0.05	0.05	0.05	N/A	N/A	0.05	0.05
Aug	0.35	0.35	0.35	0.35	N/A	N/A	0.35	0.35
Sep	0.4	0.4	0.4	0.4	N/A	N/A	0.4	0.4
Oct	0.4	0.4	0.4	0.4	N/A	N/A	0.4	0.4
Nov	0.4	0.4	0.4	0.4	N/A	N/A	0.4	0.4
Dec	0.4	0.4	0.4	0.4	N/A	N/A	0.4	0.4

Lower Zone Evapo-transpiration Monthly Table

	WELL DRAINED TILL	WELL DRAINED SAND	WELL DRAINED CLAY LOAM	POORLY DRAINED TILL (LOWLAND GLACIOFLUVIAL)	POORLY DRAINED SAND (LOWLAND GLACIOLACUSTRINE)	POORLY DRAINED CLAY LOAM (LOWLAND GLACIAL)	ORGANIC	IMPERVIOUS (FRACTURED ROCK TREATED AS PERVIOUS)
Jan	0.3	0.3	0.3	0.01	N/A	N/A	0.3	0.3
Feb	0.5	0.5	0.5	0.01	N/A	N/A	0.5	0.5
Mar	0.6	0.6	0.6	0.01	N/A	N/A	0.6	0.6
Apr	0.8	0.8	0.8	0.1	N/A	N/A	0.8	0.8
May	0.2	0.2	0.2	0.1	N/A	N/A	0.2	0.1
Jun	0.2	0.2	0.2	0.1	N/A	N/A	0.2	0.1
Jul	0.2	0.2	0.2	0.1	N/A	N/A	0.2	0.2
Aug	0.4	0.4	0.4	0.1	N/A	N/A	0.4	0.4
Sep	0.5	0.5	0.5	0.1	N/A	N/A	0.5	0.5
Oct	0.5	0.5	0.5	0.1	N/A	N/A	0.5	0.2
Nov	0.5	0.5	0.5	0.1	N/A	N/A	0.5	0.2
Dec	0.6	0.6	0.6	0.01	N/A	N/A	0.6	[illegible]

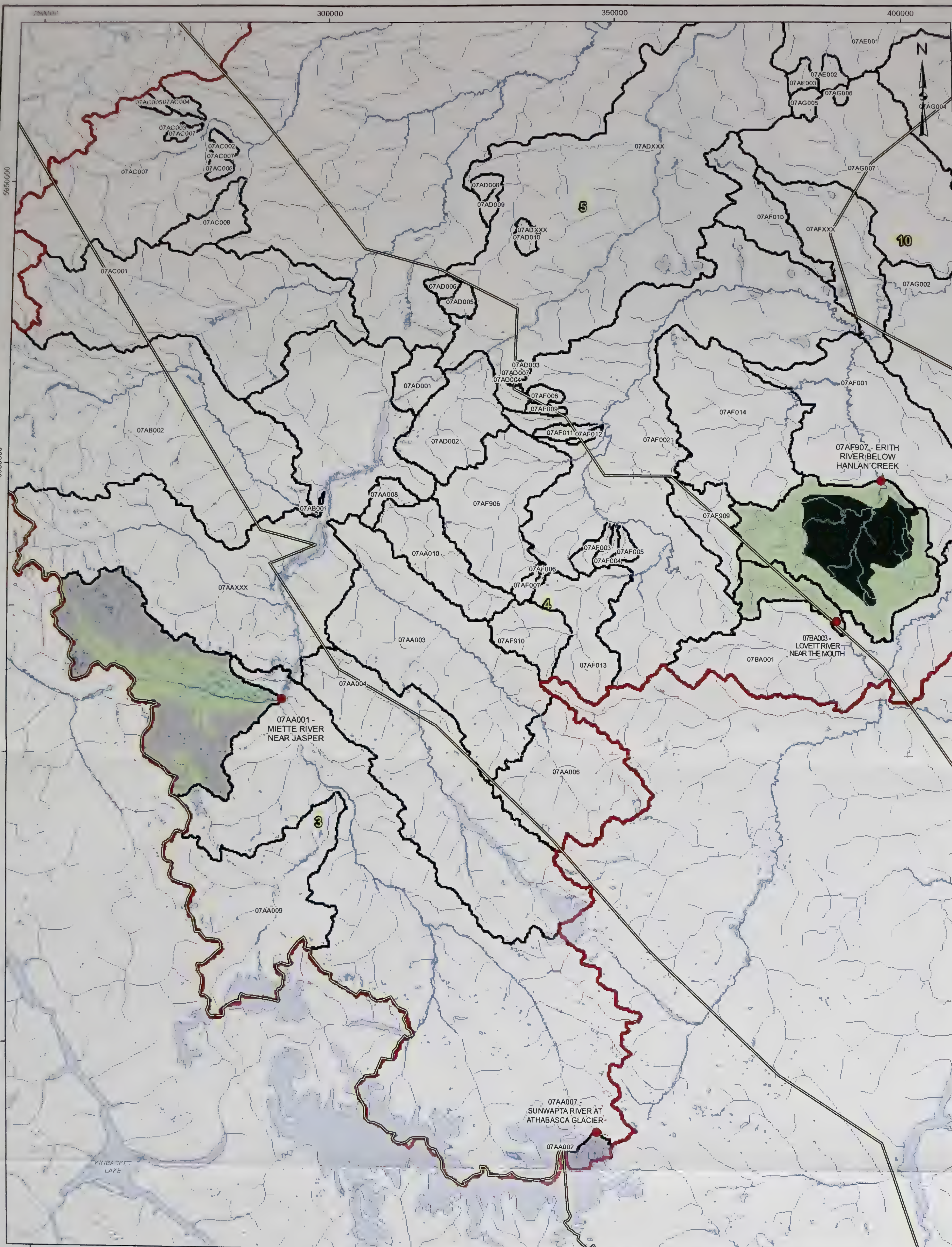
Table 4.3 Calibrated HSPF Model Parameters for the Athabasca and Beaver River Basins (continued)

Table 4.3b HSPF Model Parameters (Water) - IMPLND

Water Parameter	Meaning	Units	GLACIER
NSUR	Manning's n for the overland flow plane	none	1
RETSC	The retention (interception) storage capacity of the surface.	in	0
PETMAX	The air temperature below which E-T will arbitrarily be reduced below the value obtained from the input time series.	degF	48
PETMIN	The temperature below which E-T will be zero regardless of the value in the input time series.	degF	40
RETS	The initial retention storage.	in	0.001
SURS	The initial surface (overland flow) storage.	in	0.001

Table 4.3c HSPF Model Parameters (Snow)

Snow Parameter	Description	Units	WELL DRAINED TILL	WELL DRAINED SAND	WELL DRAINED CLAY LOAM	POORLY DRAINED TILL (LOWLAND GLACIOFLUVIAL)	POORLY DRAINED SAND (LOWLAND GLACIOLACUSTRINE)	POORLY DRAINED CLAY LOAM (LOWLAND GLACIAL)	ORGANIC	IMPERVIOUS (TREATED AS PERVIOUS)	GLACIER (IMPERVIOUS)
LAT	Latitude	Degree	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3 (57.5)	54.3
SHADE	Fraction of the land which is shaded from solar radiation by trees	none	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.66
SNOWCF	Factor by which the input precipitation data will be multiplied	none	1	1	1	1	1	1	1	1	1
COVIND	Maximum snow pack (water equivalent) at which the entire land will be covered with snow	none	10	5	5	5	5	5	5	3	8.8
KMELT	Constant degree-day factor for the temperature index snow melt method	in/day.F	0	0	0	0	0	0	0	0	0
TBASE	Reference temperature for the temperature index method	degF	32	32	32	32	32	32	32	32	32
RDCSN	Density of cold, new snow relative to water	none	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
TSNOW	Air temperature below which precipitation will be snow	degF	40	40	40	40	40	40	37	40	30.2
SNOEVP	Parameter which adapts the snow evaporation (sublimation) equation to field conditions	none	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.25	0.0003
CCFACT	Parameter which adapts the snow condensation/convection melt equation to field conditions.	none	0.1 (0.2)	0.1	0.1	0.1	0.1	0.1	0.1	0.1 (0.2)	0.677
MWATER	Maximum water content of the snow pack, in depth of water per depth of water	none	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.25	0.005
MGMELT	Maximum rate of snow melt by ground heat, in depth of water per day	in/day	0.02	0.02	0.02	0.02	0.02	0.02	0	0.02	0
PACK-ICE	Quantity of ice in the pack (water equivalent)	inch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000



LEGEND

- HYDROMETRIC STATION
- WATERCOURSE
- HYDROLOGIC REGION
- STUDY AREA
- SUB-BASIN
- WATERBODY

SOIL TYPE

- IMPERVIOUS
- ORGANIC
- POORLY DRAINED CLAY LOAM
- POORLY DRAINED SAND
- POORLY DRAINED TILL
- RAPIDLY DRAINED SAND
- RAPIDLY DRAINED TILL
- WELL DRAINED CLAY LOAM
- WELL DRAINED SAND
- WELL DRAINED TILL

20 0 20

SCALE 1:650,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from AENV; gross drainage areas combined with previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Surficial Geology obtained from Government of Canada / Agriculture and Agri-Food Canada (GC/AAFC).
Projection: Alberta 10TM False Easting 500000.000 at 115° W Datum: NAD 83

PROJECT

Government of Alberta Environment

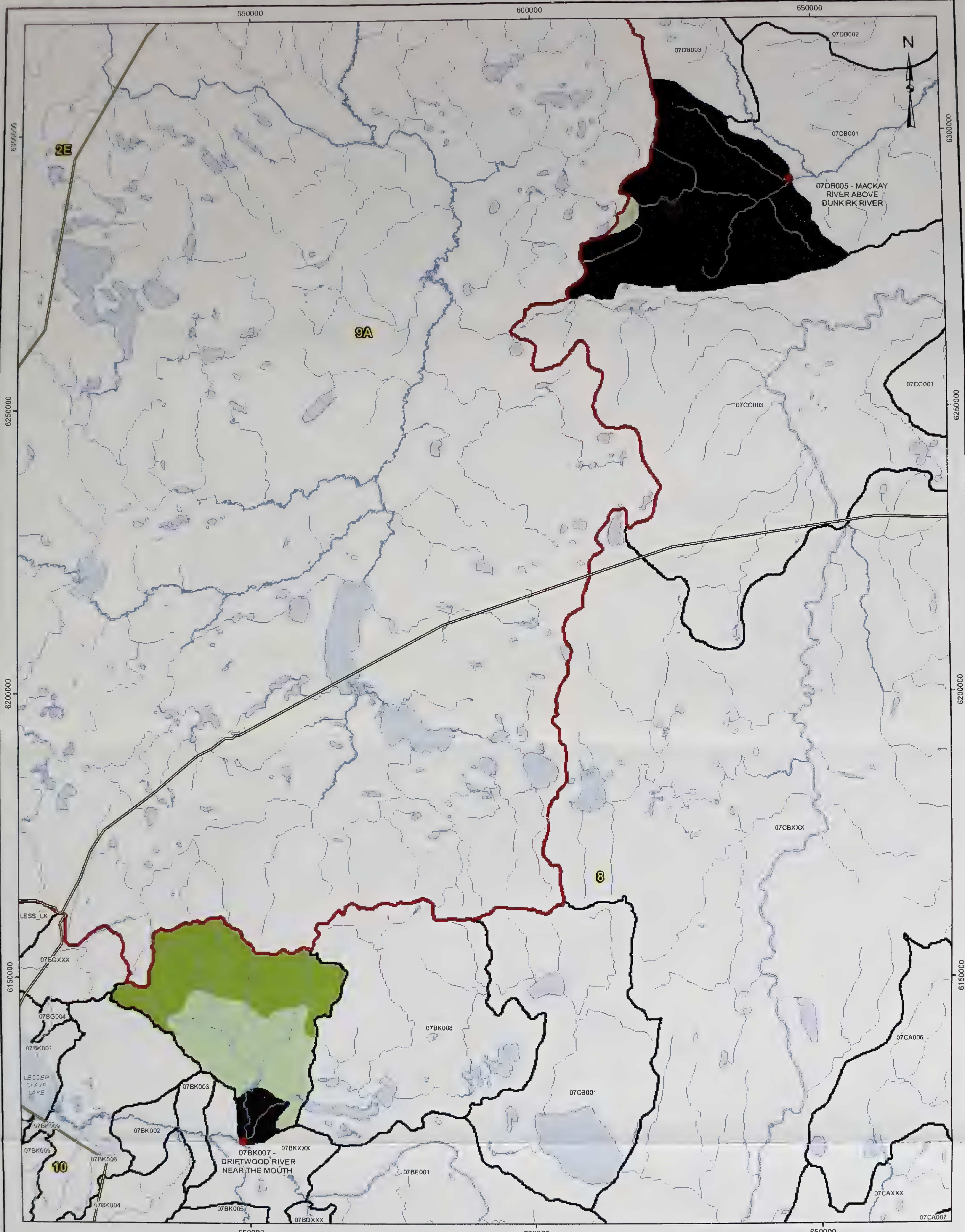
HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

SURFICIAL GEOLOGY OF ERITH, LOVETT, SUNWAPTA AND MIETTE RIVER SUB-BASINS

Golder Associates
Calgary, Alberta

PROJECT No. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	19 May 2009	**FIGURE: 4.1**	
GIS	PT	26 Jun 2009		
CHECK	AB	05 Aug 2009		
REVIEW	AB	05 Aug 2009		



LEGEND

- HYDROMETRIC STATION
- WATERCOURSE
- HYDROLOGIC REGION
- STUDY AREA
- SUB-BASIN
- WATERBODY

SOIL TYPE

- IMPERVIOUS
- ORGANIC
- POORLY DRAINED CLAY LOAM
- POORLY DRAINED SAND
- POORLY DRAINED TILL
- RAPIDLY DRAINED SAND
- RAPIDLY DRAINED TILL
- WELL DRAINED CLAY LOAM
- WELL DRAINED SAND
- WELL DRAINED TILL

20 0 20

SCALE 1:650,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from ... gross drainage areas combined with previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Surficial Geology obtained from Government of Canada / Agriculture and Agri-Food Canada (GC/AAFC). Projection: Alberta 10TM False Easting 500000 at 115° W Datum: NAD 83

PROJECT
Government of Alberta Environment

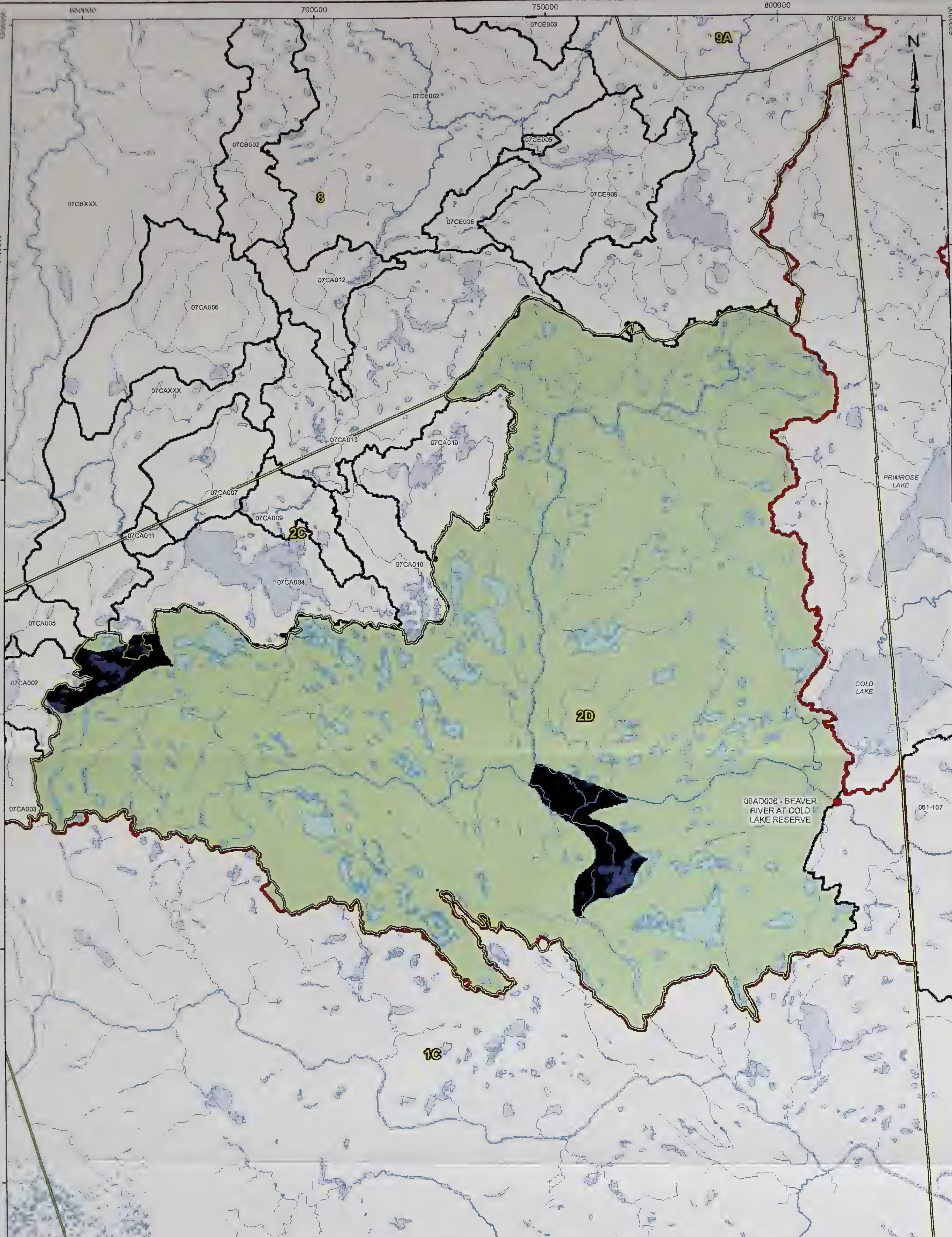
HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

SURFICIAL GEOLOGY OF DRIFTWOOD AND MACKAY RIVER SUB-BASINS

Golder Associates
Calgary, Alberta

PROJECT No. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	19 May 2009		
GIS	PT	26 Jun 2009		
CHECK	AB	05 Aug 2009	FIGURE: 4.2	
REVIEW	AB	05 Aug 2009		



LEGEND

- HYDROMETRIC STATION
- WATERCOURSE
- HYDROLOGIC REGION
- STUDY AREA
- SUB-BASIN
- WATERBODY

SOIL TYPE

- IMPERVIOUS
- ORGANIC
- POORLY DRAINED CLAY LOAM
- POORLY DRAINED SAND
- POORLY DRAINED TILL
- RAPIDLY DRAINED SAND
- RAPIDLY DRAINED TILL
- WELL DRAINED CLAY LOAM
- WELL DRAINED SAND
- WELL DRAINED TILL

25 0 25

SCALE 1:800,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from PFRA gross drainage areas combined with previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Surficial Geology obtained from Government of Canada / Agriculture and Agri-Food Canada (GC/AAFC). Projection: Alberta 10TM False Easting 500,000 at 115 ° W Datum NAD 83

PROJECT

Government of Alberta
Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

SURFICIAL GEOLOGY OF BEAVER RIVER SUB-BASIN

Golder Associates
Calgary, Alberta

PROJECT No. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	19 May 2009	FIGURE: 4.3	
GIS	PT	26 Jun 2009		
CHECK	AB	05 Aug 2009		
REVIEW	AB	05 Aug 2009		

- Model parameters for the Well/Rapidly Drained Sand land type were calibrated using the recorded stream flows at Driftwood River near the Mouth (Environment Canada Hydrometric Station 07BK007). The surficial geology of the Driftwood River sub-basin is approximately 56% Well/Rapidly Drained Till, 3% Organic, and 41% Well/Rapidly Drained Sand (see Figure 4.2). During the calibration process, the model parameters for the Well/Rapidly Drained Till and Organic land types were transferred from those obtained during the calibration of the Lovett River and Mackay River above Dunkirk River sub-basins, respectively. The precipitation data used were from the Slave Lake climate station.

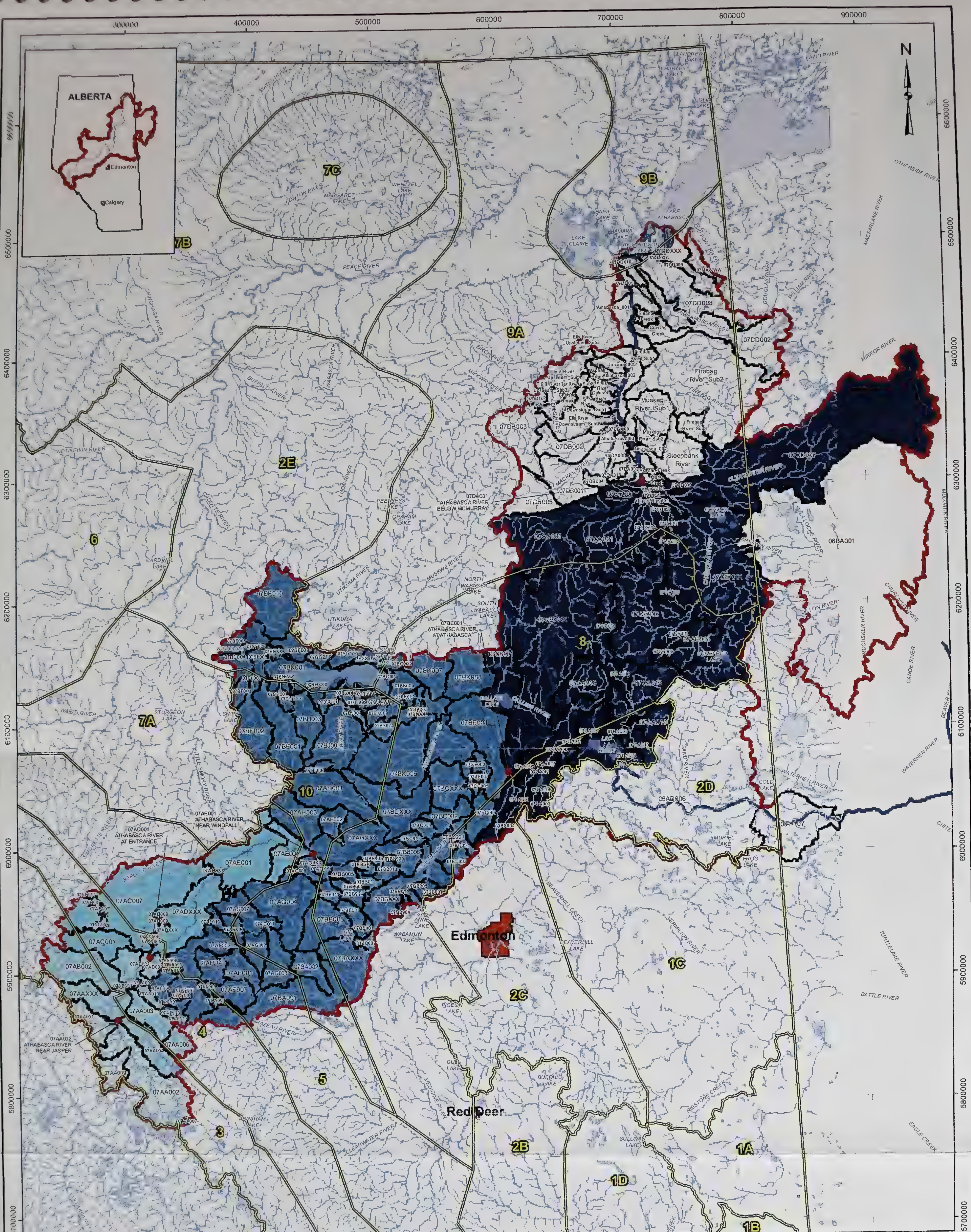
- Model parameters for the Beaver River at Cold Lake Reserve sub-basin (Environment Canada Hydrometric Station 06AD006) were initially assumed to be the same as for the Well/Rapidly Drained Till land type as obtained during the calibration of the Lovett River sub-basin. The entire Beaver River watershed was assumed to be covered by Well/Rapidly Drained Till (see Figure 4.3). The calibration of the Beaver River Basin was fine tuned using recorded flows on the basin because the basin has a hydrologic response that is significantly different from most of the sub-basins in the Athabasca River Basin due to the significant portions of the basin being classified as non-contributing during storms with a frequency of more than two years. The precipitation data used were from the Cold Lake climate station.

- Model parameters for the Poorly Drained Till (Lowland Glaciofluvial), Poorly Drained Sand (Lowland Glaciolacustrine), and Poorly Drained Clay Loam (Lowland Glacial) land types were obtained from a report on Regional Surface Water Hydrology Study for Re-Calibration of HSPF Model (Golder 2003).

The sub-basins used for validation are listed in Table 4.2 and shown in Figure 4.4. The validation of the calibrated HSPF model was based on a comparison of observed and simulated flows at gauging stations on the main stem of the Athabasca River, namely, Athabasca River near Jasper (Environment Canada Hydrometric Station 07AA002), Athabasca River at Hinton (Environment Canada Hydrometric Station 07AD002), Athabasca River near Windfall (Environment Canada Hydrometric Station 07AE001), Athabasca River at Athabasca (Environment Canada Hydrometric Station 07BE001), Athabasca River below McMurray (Environment Canada Hydrometric Station 07DA001), and Clearwater River at Draper (Environment Canada Hydrometric Station 07CD001). Model parameters for the Clearwater River at Draper (Environment Canada Hydrometric Station 07CD001) were calibrated and validated separately as most of the sub-basin lies within the province of Saskatchewan and the land type information was not available. The portion of the Clearwater River sub-basin with missing surficial geology data was assumed to be covered by rapidly drained sand (i.e., extending the surficial geology data available on the province of Alberta side of the border), and the calibration/validation was done using recorded stream flow data.

The accuracy of the model calibration and validation was evaluated by comparing the measured and simulated flow parameters listed below:

- Mean annual flow;
- Mean open water (March to October) flow;
- Mean monthly flow (12 months); and,
- 2-, 10-, and 25-year peak flood flows. The 2, 10, and 25-yr flood flows were estimated from the "best-fit" probability distribution function to the annual peak flow series. The available probability distribution functions were the Three-Parameter Lognormal, General Extreme Value, and Log Pearson III distributions. The "best fit" distribution was based on the minimum sum of squares of differences between the data and the theoretical fits.



LEGEND

●	HYDROMETRIC STATION		SUB-BASIN VALIDATION
	HYDROLOGIC REGION		07AA002 - ATHABASCA RIVER NEAR JASPER
	WATERBODY		07AD002 - ATHABASCA RIVER AT HINTON
	WATERCOURSE		07AE001 - ATHABASCA RIVER NEAR WINDFALL
	STUDY AREA		07BE001 - ATHABASCA RIVER AT ATHABASCA
	SUB-BASIN		07DA001 - ATHABASCA RIVER BELOW MCMURRAY
			ATHABASCA RIVER
			CITY

100 0 100

SCALE 1:3,000,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from ... gross drainage areas combined with previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Surficial Geology obtained from Government of Canada / Agriculture and Agri-Food Canada (GC/AAFC).
Projection: Alberta 10TM False Easting 500 000 at 115° W Datum: NAD 83

PROJECT

Government of Alberta Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

SUB-BASINS USED IN THE VALIDATION OF CALIBRATED HSPF MODEL PARAMETERS

Golder Associates
Calgary, Alberta

PROJECT NO. 08-1326-0033			SCALE AS SHOWN
DESIGN	OK	20 May 2009	
GIS	PT	26 Jun 2009	
CHECK	AB	05 Aug 2009	
REVIEW	AB	05 Aug 2009	

REV. 0

FIGURE: 4.4

4.2.1.5 Model Calibration and Validation Statistics

A comparison of the statistics of the simulated flow series from the calibration and validation of HSPF with the statistics of the observed series is provided in Appendix E. Observed and simulated annual hydrographs are provided therein for selected time periods. Comparisons of simulated and observed mean monthly flows on the six gauged sub-basins used for calibration, each dominated by one particular land type, are shown in Figure 4.5. Figure 4.6 shows the mean monthly flow comparisons for the seven sub-basins used for validation of the calibrated HSPF model.

The outcome of the calibration and validation of the HSPF model was deemed to be good to reasonable to poor based on the following criteria:

- Good:
  - Observed mean annual flow or mean open-water flow replicated to less than 10%; and,
  - Mean monthly flows replicated to within 20%, except for winter (very low flow) months when a difference of less than 40% was deemed to be good.
- Reasonable:
  - Observed mean annual flow or mean open-water flow replicated to less than 15%; and,
  - Mean monthly flows replicated to within 40%, except for winter (very low flow) months when a difference of less than 60% was deemed to be reasonable.
- Poor:
  - Difference between observed and simulated mean annual flows is more than 15%; and,
  - Difference between observed and simulated mean monthly flows is greater than 40%, and greater than 60% for winter (very low flow) months.

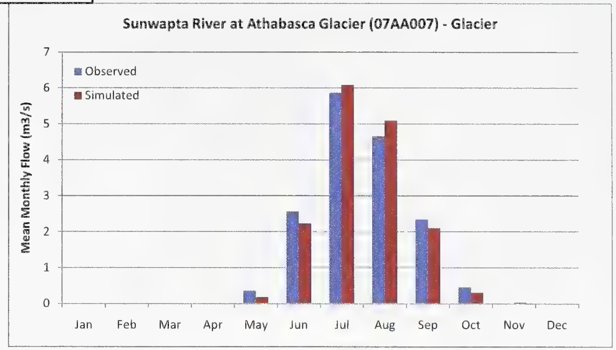
Figure 4.5 Comparison of Simulated and Observed Mean Monthly Flows on Calibration Sub-Basins

Simulated and recorded flow statistics for Sunwapta River at Athabasca Glacier Station 07AA007) - Calibration (Glacier) (1994-1996)

	Calibration		
Statistic	**Recorded**	**Simulated**	Diff (%)
Mean Annual Flow (m^3/s)			
Mean Open-Water Flow (m^3/s)	2.71	2.67	-1%
2-Year Peak Flow (m^3/s)	10.4	11.4	10%
10-Year Peak Flow (m^3/s)	10.9	15.4	41%
25-Year Peak Flow (m^3/s)	11.2	16.9	52%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan		0.00	
Feb		0.00	
Mar		0.00	
Apr		0.00	
May	0.36	0.18	-49%
Jun	2.56	2.23	-13%
Jul	5.9	6.09	4%
Aug	4.66	5.09	9%
Sep	2.34	2.10	-10%
Oct	0.46	0.31	-33%
Nov		0.03	
Dec		0.01	

Note: [1] Open water season is from May to October.

Figure 4.5a

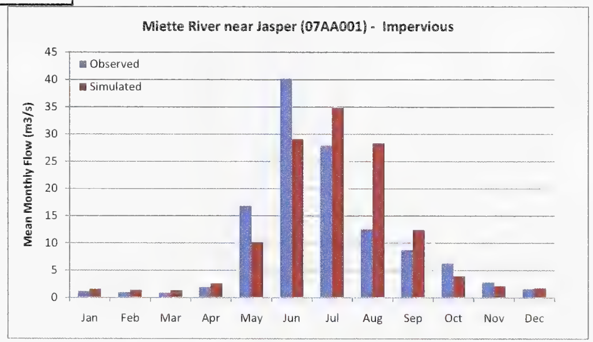


Simulated and recorded flow statistics for Miette River near Jasper Station 07AA001) - Calibration (Impervious/Fractured Rock) (1995-2006)

	Calibration		
Statistic	**Recorded**	**Simulated**	Diff (%)
Mean Annual Flow (m^3/s)	10.2	10.8	6%
Mean Open-Water Flow (m^3/s)	16.4	17.4	6%
2-Year Peak Flow (m^3/s)	67.0	62.7	-6%
10-Year Peak Flow (m^3/s)	92.1	91.2	-1%
25-Year Peak Flow (m^3/s)	104	104	0%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan	1.21	1.54	27%
Feb	1.01	1.42	40%
Mar	0.92	1.34	45%
Apr	1.97	2.63	34%
May	16.9	10.16	-40%
Jun	40.1	29.1	-28%
Jul	27.9	34.9	25%
Aug	12.6	28.3	125%
Sep	8.80	12.44	41%
Oct	6.32	3.98	-37%
Nov	2.85	2.13	-25%
Dec	1.69	1.73	2%

Note: [1] Open water season is from April to October.

Figure 4.5b



Golder Associates

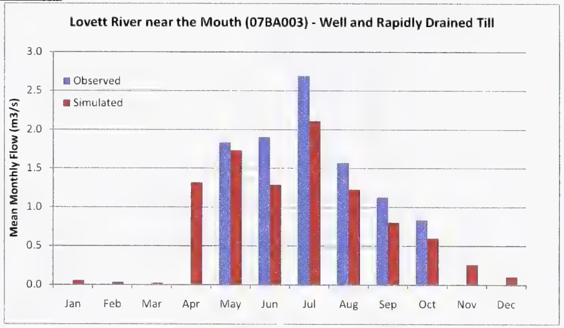
Figure 4.5 Comparison of Simulated and Observed Mean Monthly Flows on Calibration Sub-Basins (continued)

Simulated and recorded flow statistics for Lovett River near the Mouth Station 07BA003) - Calibration (Well and Rapidly Drained Till) (1982-1991)

Statistic	Calibration Recorded	Calibration Simulated	Diff (%)
Mean Annual Flow (m^3/s)			
Mean Open-Water Flow (m^3/s)	1.7	1.29	-22%
2-Year Peak Flow (m^3/s)	12.0	9.15	-24%
10-Year Peak Flow (m^3/s)	33.0	31.5	-5%
25-Year Peak Flow (m^3/s)	44.9	53.3	19%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan		0.05	
Feb		0.03	
Mar		0.02	
Apr		1.32	
May	1.83	1.73	-6%
Jun	1.90	1.29	-32%
Jul	2.7	2.11	-22%
Aug	1.57	1.23	-22%
Sep	1.13	0.80	-29%
Oct	0.83	0.60	-28%
Nov		0.26	
Dec		0.10	

Note: [1] Open water season is from May to October.
[2] There is no recorded flow data during winter season.

Figure 4.5c



Simulated and recorded flow statistics for Erith River below Hanlan Creek Station 07AF907) - Calibration (Well Drained Clay Loam) (1984-1990)

Statistic	Calibration Recorded	Calibration Simulated	Diff (%)
Mean Annual Flow (m^3/s)			
Mean Open-Water Flow (m^3/s)	6.6	6.70	2%
2-Year Peak Flow (m^3/s)	48.7	70.9	46%
10-Year Peak Flow (m^3/s)	199	276	39%
25-Year Peak Flow (m^3/s)	444	457	3%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan		0.20	
Feb		0.12	
Mar		0.08	
Apr		8.09	
May	6.97	7.72	11%
Jun	6.53	5.67	-13%
Jul	11.0	11.64	6%
Aug	6.67	7.02	5%
Sep	5.04	4.68	-7%
Oct	3.22	3.48	8%
Nov		1.22	
Dec		0.43	

Note: [1] Open water season is from May to October.
[2] There is no recorded flow data during winter season.

Figure 4.5d

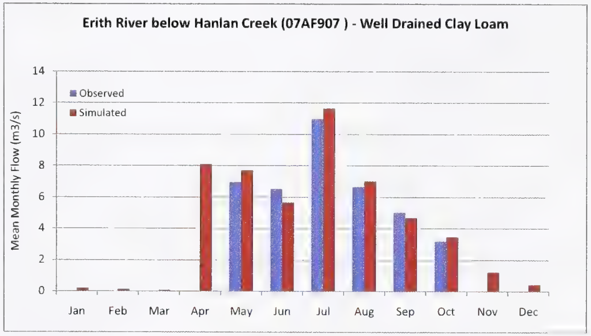


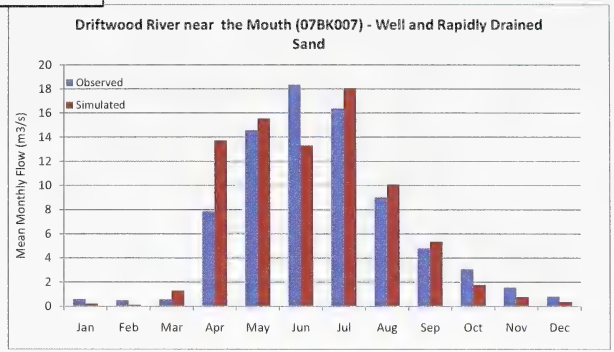
Figure 4.5 Comparison of Simulated and Observed Mean Monthly Flows on Calibration Sub-Basins (continued)

Simulated and recorded flow statistics for Driftwood River near the Mouth Station 07BK007) (1987-1998) - Calibration (Well and Rapidly Drained Sand)

Statistic	Calibration Recorded	Calibration Simulated	Diff (%)
Mean Annual Flow (m^3/s)	6.51	6.72	3%
Mean Open-Water Flow (m^3/s)	10.6	11.1	5%
2-Year Peak Flow (m^3/s)	55.7	43.9	-21%
10-Year Peak Flow (m^3/s)	154	162	5%
25-Year Peak Flow (m^3/s)	231	284	23%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan	0.59	0.20	-66%
Feb	0.50	0.13	-75%
Mar	0.56	1.30	134%
Apr	7.87	13.73	75%
May	14.58	15.56	7%
Jun	18.37	13.31	-28%
Jul	16.38	18.07	10%
Aug	9.02	10.08	12%
Sep	4.81	5.35	11%
Oct	3.09	1.76	-43%
Nov	1.56	0.77	-50%
Dec	0.83	0.35	-57%

Note: [1] Open water season is from April to October.

Figure 4.5e



Simulated and recorded flow statistics for Mackay River above Dunkirk River Station 07DB005) - Calibration (Organic Soil) (1983-1990)

Statistic	Calibration Recorded	Calibration Simulated	Diff (%)
Mean Annual Flow (m^3/s)			
Mean Open-Water Flow (m^3/s)	3.7	3.48	-5%
2-Year Peak Flow (m^3/s)	19.9	21.8	9%
10-Year Peak Flow (m^3/s)	41.4	41.4	0%
25-Year Peak Flow (m^3/s)	50.1	51.0	2%
Mean Monthly Flows (m^3/s)			
Month	Observed	Simulated	
Jan		0.26	
Feb		0.20	
Mar	0.04	0.15	273%
Apr	2.67	2.08	-22%
May	7.63	7.81	2%
Jun	7.29	5.85	-20%
Jul	6.6	6.81	2%
Aug	2.36	3.32	41%
Sep	1.17	1.12	-5%
Oct	1.58	0.73	-54%
Nov		0.52	
Dec		0.36	

Note: [1] Open water season is from March to October.
[2] There is no recorded flow data during winter season.

Figure 4.5f

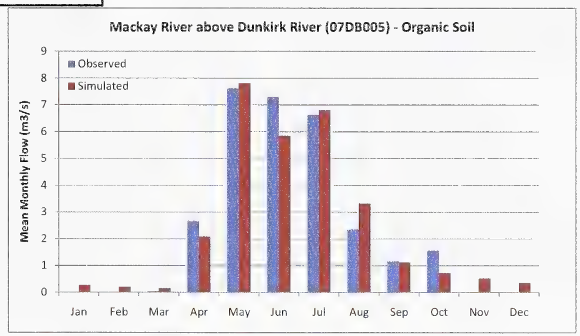


Figure 4.5 Comparison of Simulated and Observed Mean Monthly Flows on Calibration Sub-Basins (continued)

Simulated and recorded flow statistics for Beaver River at Cold Lake Reserve (06AD006)

Figure 4.5g

Statistic	Validation: Recorded (1968-1987)	Validation: Simulated (1968-1987)	% Diff
Mean Annual Flow (m^3/s)	20.8	22.0	5.9%
Mean Open-Water Flow (m^3/s)	31.6	32.5	2.9%
2-Year Peak Flow (m^3/s)	100	78.9	-21.3%
10-Year Peak Flow (m^3/s)	249	220	-11.5%
25-Year Peak Flow (m^3/s)	347	331	-4.7%
Mean Monthly Flows (m^3/s)			
Jan	4.30	5.92	37.8%
Feb	4.04	4.87	20.6%
Mar	4.78	7.10	48.6%
Apr	41.7	42.5	2.0%
May	50.5	58.5	15.8%
Jun	32.6	32.5	-0.4%
Jul	37.9	35.7	-5.9%
Aug	22.0	22.7	3.2%
Sep	19.1	17.4	-8.6%
Oct	17.2	18.0	5.0%
Nov	9.53	11.0	15.5%
Dec	5.58	7.65	37.1%

Note: [1] Open water season is from April to October.

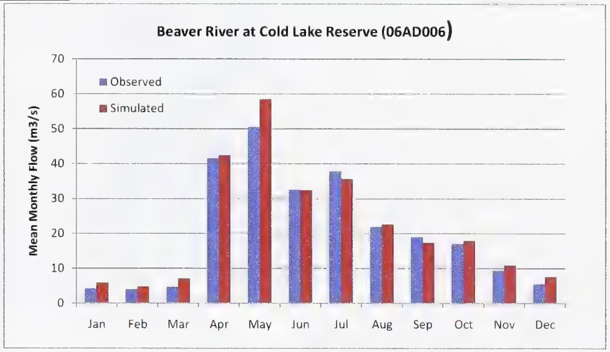


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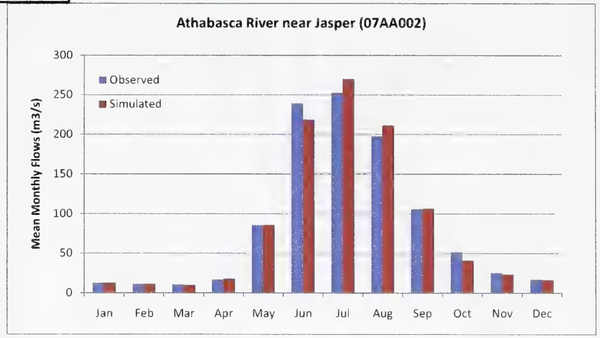
Figure 4.6 Comparison of Simulated and Observed Mean Monthly Flows on Validation Sub-Basins

Simulated and recorded flow statistics for Athabasca River near Jasper (07AA002)

Statistic	Validation: Recorded (1971-2005)	Validation: Simulated (1971-2005)	% Diff
Mean Annual Flow (m^3/s)	85.6	85.4	0%
Mean Open-Water Flow (m^3/s)	136	136	0%
2-Year Peak Flow (m^3/s)	410	356	-13%
10-Year Peak Flow (m^3/s)	553	409	-26%
25-Year Peak Flow (m^3/s)	617	428	-31%
Mean Monthly Flows (m^3/s)			
Jan	12.8	12.5	-2%
Feb	11.3	11.4	1%
Mar	10.8	10.1	-6%
Apr	16.8	17.9	6%
May	85.4	85.7	0%
Jun	239	219	-9%
Jul	253	270	7%
Aug	198	212	7%
Sep	106	106.3	0%
Oct	51.8	40.8	-21%
Nov	25.4	23.3	-9%
Dec	17.1	16.5	-3%

Note: [1] Open water season is from April to October.

Figure 4.6a



Simulated and recorded flow statistics for Athabasca River at Hinton (Station 07AD002)

Statistic	Validation: Recorded (1962-2005)	Validation: Simulated (1962-2005)	% Diff
Mean Annual Flow (m^3/s)	172	172	0%
Mean Open-Water Flow (m^3/s)	265	271	2%
2-Year Peak Flow (m^3/s)	786	932	19%
10-Year Peak Flow (m^3/s)	1041	1247	20%
25-Year Peak Flow (m^3/s)	1146	1349	18%
Mean Monthly Flows (m^3/s)			
Jan	36.0	27.5	-24%
Feb	32.5	29.7	-9%
Mar	32.1	26.1	-19%
Apr	44.4	43.6	-2%
May	174	175	1%
Jun	488	449	-8%
Jul	472	553	17%
Aug	349	398	14%
Sep	211	202	-4%
Oct	117	79.1	-33%
Nov	60.6	45.7	-24%
Dec	42.9	34.2	-20%

Note: [1] Open water season is from April to October.

Figure 4.6b

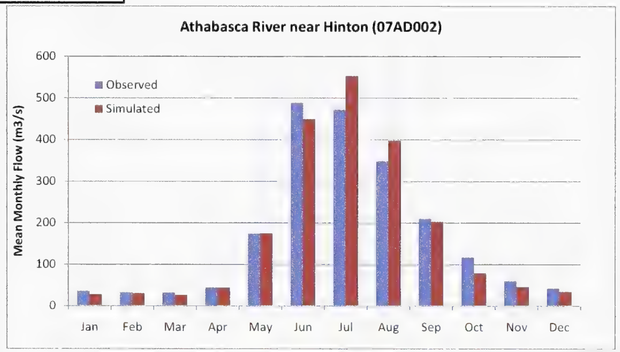


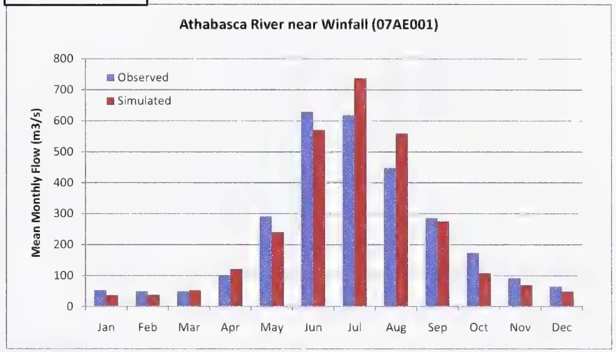
Figure 4.6 Comparison of Simulated and Observed Mean Monthly Flows on Validation Sub-Basins (continued)

Simulated and recorded flow statistics for Athabasca River near Windfall (Station 07AE001)

Statistic	Validation Recorded (1962-2005)	Validation Simulated (1962-2005)	% Diff
Mean Annual Flow (m^3/s)	238	238	0%
Mean Open-Water Flow (m^3/s)	364	373	3%
2-Year Peak Flow (m^3/s)	1113	1156	4%
10-Year Peak Flow (m^3/s)	1618	1695	5%
25-Year Peak Flow (m^3/s)	1859	1949	5%
Mean Monthly Flows (m^3/s)			
Jan	53.0	36.9	-30%
Feb	49.7	38.6	-22%
Mar	49.9	52.4	5%
Apr	102	122	19%
May	292	241	-18%
Jun	629	570	-9%
Jul	618	738	19%
Aug	448	559	25%
Sep	287	275	-4%
Oct	174	108.5	-37%
Nov	92.8	69.6	-25%
Dec	64.4	49.2	-24%

Note: [1] Open water season is from April to October.

Figure 4.6c



Simulated and recorded flow statistics for Athabasca River at Athabasca (Station 07BE001)

Statistic	Validation Recorded (1962-2005)	Validation Simulated (1962-2005)	% Diff
Mean Annual Flow (m^3/s)	429	432	1%
Mean Open-Water Flow (m^3/s)	652	654	0%
2-Year Peak Flow (m^3/s)	1916	1659	-13%
10-Year Peak Flow (m^3/s)	3271	2547	-22%
25-Year Peak Flow (m^3/s)	4051	3030	-25%
Mean Monthly Flows (m^3/s)			
Jan	100	101	1%
Feb	93	95	2%
Mar	103	130	26%
Apr	343	391	14%
May	651	549	-16%
Jun	994	881	-11%
Jul	1057	1168	11%
Aug	710	849	20%
Sep	485	484	0%
Oct	322	252	-22%
Nov	178	159	-11%
Dec	118	122	4%

Note: [1] Open water season is from April to October.

Figure 4.6d

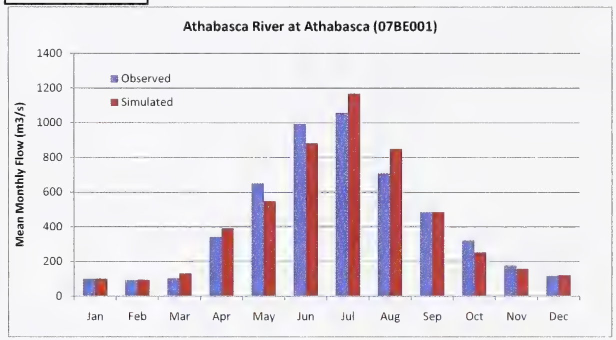


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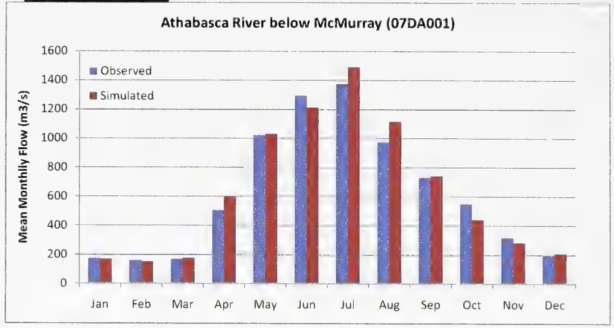
Figure 4.6 Comparison of Simulated and Observed Mean Monthly Flows on Validation Sub-Basins (continued)

Recorded and simulated flow statistics for Athabasca River below McMurray (Station 07DA001)

Statistic	Validation (1961-2007) Recorded	Simulated	Diff (%)
Mean Annual Flow (m^3/s)	623	635	2%
Mean Open-Water Flow (m^3/s)	922	948	3%
2-Year Peak Flow (m^3/s)	2345	2064	-12%
10-Year Peak Flow (m^3/s)	3647	3153	-14%
25-Year Peak Flow (m^3/s)	4309	3757	-13%
Mean Monthly Flows (m^3/s)			
Jan	174	168	-3%
Feb	160	150	-6%
Mar	168	175	4%
Apr	504	600	19%
May	1023	1030	1%
Jun	1295	1214	-6%
Jul	1378	1493	8%
Aug	975	1115	14%
Sep	731	741	1%
Oct	550	442	-20%
Nov	319	282	-11%
Dec	198	207	4%

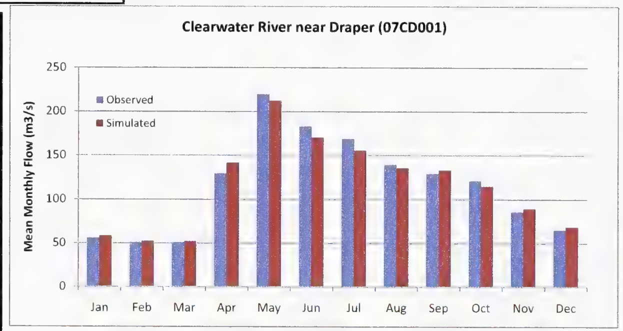
Figure 4.6e



Recorded and simulated flow statistics for Clearwater River at Draper (Station 07CD001)

Statistic	Validation (1961-2007) Recorded	Simulated	Diff (%)
Mean Annual Flow (m^3/s)	117	115	-1%
Mean Open-Water Flow (m^3/s)	156	152	-3%
2-Year Peak Flow (m^3/s)	366	371	1%
10-Year Peak Flow (m^3/s)	591	795	35%
25-Year Peak Flow (m^3/s)	689	1039	51%
Mean Monthly Flows (m^3/s)			
Jan	56.0	58.1	4%
Feb	51.0	52.1	2%
Mar	51.0	52	2%
Apr	130	142	9%
May	220	213	-3%
Jun	183	170	-7%
Jul	169	156	-8%
Aug	140	136	-3%
Sep	129	133	3%
Oct	121	115	-5%
Nov	86	89	4%
Dec	65	69	5%

Figure 4.6f



The calibration on mean annual and/or mean open-water flows is generally good for five calibration sub-basins and poor on the Lovett River sub-basin. With respect to mean monthly flows, the calibration is generally reasonable, although there are some significant differences between observed and simulated values for some winter months, which is not unexpected, and generally for the Miette River sub-basin. The reasons for some of the significant variances between observed and simulated statistics can be explained as follows. For the calibration of these sub-basins, climate data are not generally available within the sub-basin itself, instead, the data are transferred from other locations. For example, the calibration on the Driftwood River sub-basin is based on climate data recorded at Slave Lake Station (more than 40 km from the center of the sub-basin). The drainage areas of the calibration sub-basins are relatively small, and, therefore, are more likely to be subject to uncertainties due to the spatial variability in precipitation than larger basins. The timing and magnitude of actual within-basin precipitation can be different from the recorded data at the climate station used for calibration. Redistribution of snow on the landscape can have a significant influence on the rate and timing of snow melt and the soil water regime, and hence watershed yield. These processes are difficult to model, primarily because of a general lack of the required data, except perhaps in research basins. Hence, it is difficult to get good calibration for small sub-basins that are more prone to be affected by localized precipitation. In addition, climate stations tend to be located at relatively low elevations compared to the runoff-producing areas in the upper Athabasca River Basin. Extrapolating the station data to high elevation sub-basins can be problematic. For example, precipitation data at the Jasper climate station, which is located at an elevation of about 1,050 metres above sea level (masl), was used for simulation of runoff from the Miette River sub-basin. The summer and winter precipitation was adjusted using an orographic adjustment factor. More than 70% of the Miette River sub-basin is at an elevation greater than 2,000 masl, with a maximum elevation up to 2,500 masl. It is possible that extrapolation of the orographic adjustment factor to the very high elevations in this sub-basin may have resulted in some errors in the simulated runoff values. In practice, there should be a cap on the application of the orographic adjustment with elevation since rainfall amounts tend to decrease past certain elevations.

The calibration shows significant differences between observed and simulated values for winter flows in the small sub-basins because (1) there are significant uncertainties in low winter flow values and (2) small differences in magnitude usually manifest themselves as large percentage changes because the differences are divided by small winter flow values.

Other factors that may have affected the calibration of the model are spatial variability in frozen soil conditions, spatial variability in vegetation cover, land use changes over time, water withdrawals and returns, etc. Adjustments for these factors can be made within the model for specific studies on stand-alone sub-basins, however, given that the model is being implemented for the entire Athabasca River Basin with the focus on the natural flows in the lower reaches of the Athabasca River Basin, these adjustments are not considered necessary at this stage.

Further attempts at refining the calibration of the model did not result in significant improvements in model performance. Also, given that the performance of the model at the validation nodes on the main stem of the Athabasca River is considered good, the HSPF model is considered calibrated with parameters as given in Table 4.3 for the Athabasca and Beaver River basins.

Figure 4.6 and the detailed results presented in Appendix E indicate that, in general, the calibrated model reproduced the measured discharges at the validation nodes on the main stem of the Athabasca River well to reasonably well, giving confidence in the use of the model for assessing the hydrologic effects of potential future climate changes. The validation nodes capture sub-basins with different land types (in different percentages within each sub-basin as shown in Table 4.2) and different climate regime. The combination of a range of land types and climate regimes at the validation nodes is likely a more rigorous test of the performance of the calibrated model. However, it may be argued that at these nodes the drainage areas are much larger than those of the small sub-basins and differences in responses between small sub-basins tend to be "masked" out, thus improving the model performance at the validation stage. Notwithstanding the foregoing, it is concluded that the calibrated HSPF model has been validated and is appropriate for assessing the effects of climate change on the yield in the Lower Athabasca Regional Plan Area.

4.3 Summary

The HSPF model was calibrated and validated for application to the Athabasca River Basin and Beaver River Basin. Each basin was sub-divided on the basis of drainage network, locations of gauging stations, and surficial geology. Temperature and precipitation data for the calibration of the model were from climate stations closest (specific selection based on availability of concurrent climate and flow data) to the sub-basins. Seven sub-basins were selected for calibration of the model and six (located primarily on the main stem of the Athabasca River) were selected for validation of the calibrated parameters. The calibration on mean annual and/or mean open-water flows is generally good for most calibration sub-basins. With respect to mean monthly flows, the calibration is generally reasonable, although there are some significant differences between observed and simulated values for some winter months. The calibrated model reproduced the measured discharges at the validation nodes on the main stem of the Athabasca River well to reasonably well, giving confidence in the use of the model for assessing the hydrologic effects of potential future climate changes. It was concluded that the calibrated HSPF model has been validated and is appropriate for assessing the effects of climate change on the yield in the Lower Athabasca Regional Plan Area.

5.0 ASSESSMENT OF HYDROLOGIC EFFECTS OF CLIMATE CHANGE

5.1 Introduction

The effects of climate change on water yield from the basins of Alberta will affect water uses and water management in those basins. There is a need to assess the potential effects so that watershed planners can adapt their plans to take advantage of positive effects and implement mitigation measures to minimize the negative effects. Alberta is embarking on a regional planning process and the effect of climate change on watershed responses is a key consideration in that process.

5.2 Baseline Climate Conditions and Future Climate Scenarios

To address the potential effects of climate change on water yield in the Lower Athabasca Regional Plan Area (LARP), which includes the downstream portion of the Athabasca River Basin and the Beaver River Basin, the HSPF model, calibrated and validated for these two basins, has been used to simulate the hydrologic effects of forecasted future climate scenarios. An analysis of the effects of climate change depends not only on future conditions but also on the baseline climate to which the predictions are compared. The IPCC recommends that 1961 to 1990 be adopted as the climatological baseline period in impact assessments.

As a first step in addressing the potential effects of climate change on key ecosystem variables in Alberta, Alberta Environment has developed a comprehensive database (Alberta Climate Model) of thirteen climate variables (including annual mean temperature, annual maximum temperature, annual minimum temperature, annual precipitation, degree-days above a threshold, annual moisture index) from the available Environment Canada's climate records from 1961 to 1990 (Alberta Environment 2005). The Alberta Climate Model combines long-term records from weather stations with physiographic descriptors of station locations to allow the interpolation and extrapolation of values for climatic variables along gradients. Using mathematical techniques, the pattern of fixed-point climate stations has been transformed into continuous surfaces that allow the estimation of climatic variables at any point in Alberta. The Alberta Climate Model is being used in a variety of research projects (including reclamation and terrestrial vegetation). The Alberta Climate Model facilitates estimation of values for climatic variables in areas poorly represented by climatic stations as well as provides a baseline from which to estimate impacts of changes suggested for future climates.

The Alberta Climate Model is not a tool for predicting future climates, but it contains predictions for future climates. Barrow and Yu (2005) combined the climate information derived from the Alberta Climate Model with changes in climate variables predicted by a selected number of GCMs-scenarios to provide "actual future" climate scenarios for the 2020s, 2050s and 2080s. The sub-set of climate change scenarios was selected on the basis of changes in summer mean temperature and precipitation for the 2050s. The five selected scenarios represented conditions that were cooler and wetter (NCARPCM A1B), cooler and drier (CGCM2 B2(3)), warmer and wetter (HadCM3 A2(a)) and warmer and drier (CCSRNIES A1F1) than median conditions (HadCM3 B2(b)). These five scenarios bound the range of possible future climates from a number of GCMs with respect to temperature and precipitation.

Because of the differences in scale between the GCM grids (2.5° to 5.625°) and the resolution (1 km) of the Alberta Climate Model, Barrow and Yu (2005) interpolated the climate change scenarios to 0.5° latitude/longitude resolution using a bilinear two-dimensional interpolation routine. The interpolated climate change scenario was then applied to the observed baseline climatology. Each 0.5° resolution scenario grid box contains 60 grid boxes for the baseline climatology.

AENV provided Golder with the Alberta Climate Model data and average monthly temperature and precipitation predicted by five GCMs for two future periods: 2010 to 2039 (referred to as 2020s) and 2040 to 2069 (referred to as 2050s). An assessment of the effects of the 2080s scenarios was not within the scope of this study. The Alberta Climate Model provides the average monthly temperature and precipitation and represents baseline conditions for all areas of Alberta from 1961 to 1990. Average (1961-1990) monthly temperature and precipitation values are made available by AENV for grids of size of approximately 1 km by 1 km (0.0083333°) covering the entire province.

The five climate scenarios (2020s and 2050s) provided by AENV were:

- CCSRNIES_A1F1 (warmer and drier than median conditions);
- CGCM2_B23 (cooler and drier than median conditions);
- HADCM3_A2A (warmer and wetter than median conditions);
- HADCM3_B2B (median conditions); and,
- NCARPPCM_A1B (cooler and wetter than median conditions).

The average (2010-2039 and 2040-2069) monthly temperature and precipitation values are made available for the same grids as the baseline climate for the entire province.

5.3 Assessment of Climate Change Effects – Athabasca and Beaver River Basins

5.3.1 Baseline Climate for Model Simulations

The Alberta Climate Model provides only the average (1961-1990) monthly temperature and precipitation values. The HSPF model is a continuous simulation model that requires temperature and precipitation inputs as daily values. The baseline input daily series for HSPF were obtained from the records at climate stations within the Athabasca and Beaver River basins. Using the same data from which the Alberta Climate Model was derived, daily series of temperature and precipitation were compiled for six index climate stations (see map in Appendix D) in the Athabasca River Basin. The criteria used to select the index stations were: range of climate variables recorded by the station (e.g., precipitation, temperature, wind speed, etc), length of recorded data, preferable from 1960 to the present and at least covering the baseline period of 1961 to 1990, reliable/good quality data with low number of missing data, and spatial distribution to cover most of the Hydrologic Regions in Athabasca/Beaver river basins. The index climate stations are:

- Jasper Warden, covering sub-basins in Hydrologic Regions 3 and 4;
- Edson, covering sub-basins in Hydrologic Regions 5 and 10 South;
- Campsie, covering sub-basins in Hydrologic Region 8 South;
- Slave Lake, covering sub-basins in Hydrologic Regions 10 North and 8 North;
- Lac La Biche, covering sub-basins in Hydrologic Region 2C; and,
- Fort McMurray, covering sub-basins in Hydrologic Region 9A.

These stations provide good coverage of the Athabasca River Basin. The Cold Lake climate station was used as the index station for the Beaver River Basin.

Missing data at the index stations were filled in by first developing a relationship between seasonal precipitation and elevation using data at all climate stations in a Hydrologic Region, and then using the relationship to transfer climate data from nearby climate stations adjusted for elevation to the index station within the same Hydrologic Region.

5.3.2 Baseline Climate for Estimating Changes in Future Temperature and Precipitation

The baseline (1961-1990) average monthly temperature and precipitation values for each of the sub-basins included in the HSPF model were estimated as the average of the grid cell values within the sub-basins. The average data from each sub-basin was then aggregated to the corresponding "Hydrologic Region" and applied to the Index Climate Station. Elevation correction factors are then applied as necessary.

The results are provided in Appendix F.

5.3.3 Estimating Changes in Future Temperature and Precipitation

The 2020s and 2050s average monthly temperature and precipitation values for each of the sub-basins included in the HSPF model were estimated as the average of the grid cell values within the sub-basins. The average data from each sub-basin was then aggregated to the corresponding "Hydrologic Region" and applied to the Index Climate Station. Elevation correction factors are then applied as necessary. The differences between the baseline averages and the 2020s averages, and the differences between the baseline averages and the 2050s averages are shown in Appendices G and H, respectively, for each sub-basin in the Athabasca River and Beaver River Basins. The differences in precipitation are shown as the ratio of the future value to the baseline value, and the differences in temperature are shown as the future value minus the baseline value.

Table 5.1 summarizes the changes in precipitation and temperature as an average for the entire Athabasca River Basin for each climate change scenario for the 2020s and 2050s. In a very few instances, for example, change in precipitation for January using the CCSRNIES-A1F1 model/scenario, Table 5.1 shows the value as "missing". The software for processing the Climate Model data could not read the block of data for the particular month and climate model/scenario. It was not immediately apparent after some investigation where the source of the problem was within the block of data for the particular month (1680 rows x 1800 columns for each variable for each month). Because of their relative rare occurrences, the problem data block was set aside. For further modelling work, the "missing" value was replaced as the average of the available values for the two adjacent months. Figures 5.1 and 5.2 show the changes in mean annual precipitation and mean annual temperature, respectively, for the 2020s and 2050s compared to the baseline values.

Table 5.1 Change in Forecasted Mean Monthly Precipitation and Temperature Compared to Baseline Values – Athabasca River Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2020s	Change in Forecasted Mean Monthly Precipitation as a Percentage of Baseline Value												AVG
CCSRNIES-A1F1	Missing	-6%	-3%	8%	2%	-16%	-3%	-9%	4%	1%	5%	3%	-1%
CGCM2_B23	Missing	-10%	-5%	-7%	6%	9%	3%	-13%	3%	1%	12%	2%	0%
HADCM3_A2A	21%	4%	17%	6%	4%	4%	-1%	6%	-15%	7%	11%	23%	7%
HADCM3_B2B	9%	19%	-3%	13%	11%	10%	-10%	-5%	-1%	14%	1%	22%	7%
NCARPCM_A1B	-6%	-2%	5%	Missing	2%	-2%	-12%	9%	20%	8%	6%	-9%	2%
AVERAGE	8.2%	0.8%	2.2%	4.9%	4.9%	1.0%	-4.6%	-2.3%	2.2%	6.1%	7.1%	8.0%	2.8%
2050s	Change in Forecasted Mean Monthly Precipitation as a Percentage of Baseline Value												AVG
CCSRNIES-A1F1	15%	12%	20%	22%	11%	-6%	2%	-15%	6%	4%	8%	23%	9%
CGCM2_B23	0%	2%	-4%	1%	4%	6%	0%	-5%	1%	4%	13%	4%	2%
HADCM3_A2A	28%	8%	25%	13%	3%	12%	-1%	-2%	-4%	3%	18%	46%	12%
HADCM3_B2B	24%	18%	11%	31%	10%	5%	-10%	3%	8%	17%	7%	27%	13%
NCARPCM_A1B	16%	6%	13%	12%	14%	-3%	1%	15%	10%	20%	11%	17%	11%
AVERAGE	16.6%	9.1%	13.0%	16.0%	8.2%	2.7%	-1.8%	-0.7%	4.2%	9.7%	11.4%	23.5%	9.3%
2020s	Change in Forecasted Mean Monthly Temperature as a Difference relative to Baseline Value												AVG
CCSRNIES-A1F1	-0.95	-0.55	1.08	2.46	1.68	0.25	0.75	0.84	-0.07	0.07	0.69	1.35	0.63
CGCM2_B23	3.48	1.82	2.75	1.15	1.79	0.90	1.18	1.30	0.67	0.88	0.79	1.52	1.52
HADCM3_A2A	-1.51	1.28	0.36	0.20	0.58	0.81	1.74	1.54	1.46	1.08	1.45	0.72	0.81
HADCM3_B2B	-0.44	1.41	0.16	0.87	0.90	1.23	1.51	1.63	1.12	0.16	1.20	1.99	0.98
NCARPCM_A1B	2.02	0.62	0.28	Missing	1.19	0.56	0.43	Missing	0.33	0.71	1.97	1.29	0.94
AVERAGE	0.52	0.92	0.93	1.17	1.23	0.75	1.12	1.33	0.70	0.58	1.22	1.37	0.98
2050s	Change in Forecasted Mean Monthly Temperature as a Difference relative to Baseline Value												AVG
CCSRNIES-A1F1	4.16	4.10	5.06	6.27	3.76	2.68	3.54	3.22	2.14	3.39	5.64	8.26	4.35
CGCM2_B23	4.39	3.33	3.09	1.76	3.29	1.79	1.78	1.84	1.53	1.11	0.89	3.08	2.32
HADCM3_A2A	-0.98	1.29	0.45	1.08	2.23	2.21	3.62	3.32	2.79	1.65	1.83	1.70	1.77
HADCM3_B2B	1.86	2.56	1.64	1.56	1.28	1.96	2.68	3.26	2.64	1.43	2.86	3.12	2.24
NCARPCM_A1B	4.68	1.83	1.93	1.95	1.91	1.31	1.29	2.13	2.21	2.01	2.88	3.66	2.32
AVERAGE	2.83	2.62	2.43	2.52	2.49	1.99	2.58	2.75	2.26	1.92	2.82	3.96	2.60

Figure 5.1 Percent Change in Precipitation for 2020s and 2050s – Athabasca River Basin

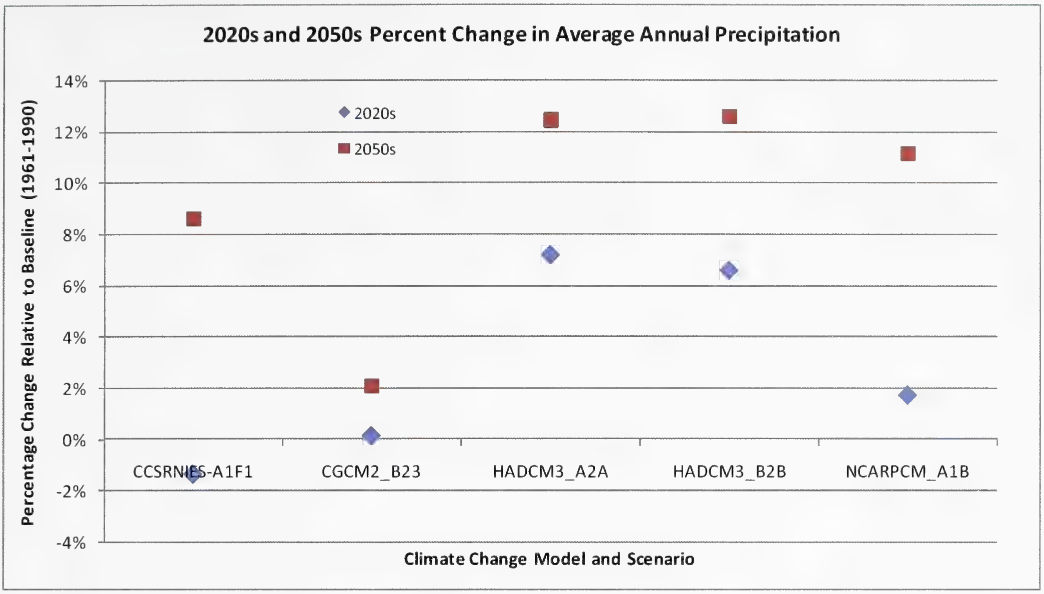


Figure 5.2 Change in Mean Annual Temperature for 2020s and 2050s – Athabasca River Basin

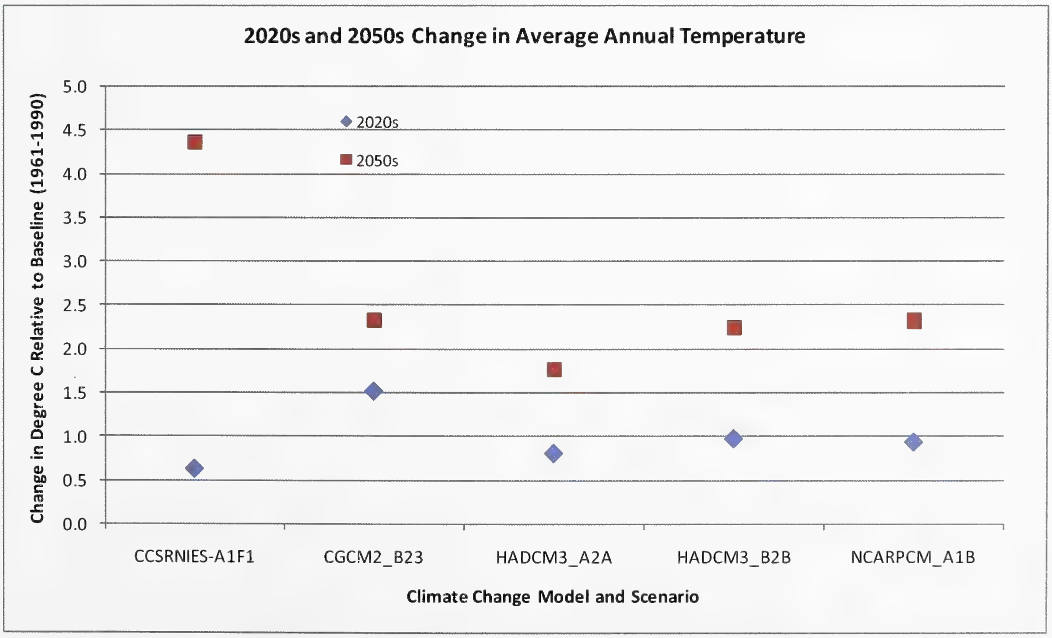


Table 5.1 shows that the average change in mean annual precipitation varies from -1% to +7% for the 2020s scenarios and from +2% to +13% for the 2050s scenarios. The range of the change in precipitation is much wider on a monthly basis: -10% to +23% for the 2020s scenarios and -15% to +46% for the 2050s scenarios. The general trend appears to be increased precipitation from the baseline period to the 2050s, but with greater variability in the monthly changes. Table 5.1 shows that the average increase in mean annual temperature varies from 0.63°C to 1.52°C for the 2020s scenarios and from 1.77°C to 4.35°C for the 2050s scenarios. The range of the change in temperature depends on the season under consideration: increases are generally greater for the fall and winter months compared to the summer months. The patterns of basin-wide annual changes due to the five scenarios do not appear to correspond precisely with the Barrow and Yu (2005) classifications, that is, CCSRNIES A1F1: warmer and drier; CGCM2 B2(3): cooler and drier; HadCM3 A2A: warmer and wetter; HadCM3 B2B: median conditions; and NCARPCM A1B: cooler and wetter. It is noted that the sub-set of climate change scenarios was selected by Barrow and Yu (2005) on the basis of changes in summer mean temperature and precipitation for the 2050s. Nevertheless, the five selected scenarios represent a range of precipitation and temperature conditions that are useful for planning purposes.

Table 5.2 summarizes the basin average changes in precipitation and temperature for the Beaver River Basin for each climate change scenario for the 2020s and 2050s. The basin average changes in mean annual precipitation and temperature in the Beaver River Basin are generally very similar to those for the Athabasca River Basin (Table 5.1), except that temperature increases appear to be higher by between 0.1°C and 0.5°C in the Beaver River Basin.

Table 5.2 Change in Forecasted Mean Monthly Precipitation and Temperature Compared to Baseline Values – Beaver River Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2020s	Change in Forecasted Mean Monthly Precipitation as a Percentage of Baseline Value												AVG
CCSRNIES-A1F1	-7%	-7%	-3%	9%	6%	-13%	-1%	-5%	3%	-1%	5%	6%	-1%
CGCM2_B23	-15%	-15%	-5%	-4%	6%	18%	9%	-11%	11%	3%	14%	10%	2%
HADCM3_A2A	19%	7%	28%	3%	6%	7%	2%	4%	-18%	3%	15%	15%	8%
HADCM3_B2B	3%	16%	-1%	14%	13%	12%	-12%	-9%	-3%	15%	1%	16%	5%
NCARPCM_A1B	-1%	6%	8%	5%	3%	-7%	-11%	8%	21%	14%	4%	-10%	3%
2050s	Change in Forecasted Mean Monthly Precipitation as a Percentage of Baseline Value												AVG
CCSRNIES-A1F1	20%	11%	15%	25%	17%	1%	11%	-5%	5%	4%	5%	22%	11%
CGCM2_B23	3%	0%	4%	9%	12%	4%	3%	-4%	10%	7%	13%	18%	7%
HADCM3_A2A	27%	14%	38%	12%	-1%	15%	0%	0%	-10%	-1%	25%	45%	14%
HADCM3_B2B	21%	13%	11%	33%	11%	7%	-9%	3%	8%	14%	4%	22%	11%
NCARPCM_A1B	23%	6%	9%	19%	13%	-4%	-6%	14%	4%	22%	5%	15%	10%
2020s	Change in Forecasted Mean Monthly Temperature as a Difference relative to Baseline Value												AVG
CCSRNIES-A1F1	-0.75	-0.57	1.12	2.90	2.14	0.34	0.80	0.97	0.00	0.19	0.78	1.53	0.79
CGCM2_B23	4.07	1.89	3.00	1.12	2.49	1.03	1.20	1.39	0.74	0.84	0.80	1.85	1.70
HADCM3_A2A	-1.22	1.34	0.34	0.30	0.60	0.98	1.81	1.60	1.69	1.19	1.47	0.82	0.91
HADCM3_B2B	-0.51	1.58	0.12	1.01	0.70	1.37	1.58	1.72	1.29	0.21	0.99	2.33	1.03
NCARPCM_A1B	2.00	0.48	-0.09	0.49	1.07	0.62	0.42	0.36	0.31	0.70	1.87	1.59	0.82
2050s	Change in Forecasted Mean Monthly Temperature as a Difference relative to Baseline Value												AVG
CCSRNIES-A1F1	4.87	4.51	5.61	7.41	4.30	2.73	3.58	3.42	2.25	3.47	5.78	8.86	4.73
CGCM2_B23	5.25	4.06	3.33	2.46	4.59	1.87	1.79	1.83	1.59	1.10	0.88	3.94	2.72
HADCM3_A2A	-0.42	1.63	0.70	1.09	2.30	2.42	3.57	3.31	3.02	1.78	2.10	1.96	1.95
HADCM3_B2B	2.18	2.82	2.26	1.95	1.17	2.12	2.69	3.22	2.79	1.53	2.97	3.84	2.46
NCARPCM_A1B	4.83	1.89	1.59	1.73	1.80	1.31	1.14	1.99	2.30	2.15	2.72	3.73	2.27

5.3.4 Future Daily Climate Scenarios

Daily 30-year series of temperature and precipitation for 2010-2039 and 2040-2069 were then generated by adjusting the baseline climate data generated as described in Section 5.3.1 by the differences estimated as described in Section 5.3.3.

5.3.5 Hydrologic Effects of Climate Change on Flows in the Athabasca and Beaver River Basins

The HSPF model calibrated for the Athabasca River Basin and Beaver River Basin was run with the baseline climate data (Section 5.3.1) and the adjusted future climate data (Section 5.3.4). A comparison of the hydrologic statistics (annual and monthly water yield particularly) at selected locations on the main stem of the Athabasca River and on the Beaver River at the Cold Lake Reserve is provided in Appendix I for the 2020s climate scenarios and in Appendix J for the 2050s climate scenarios. Summary statistics (mean annual flow, mean seasonal flows, 2-yr, 10-yr, and 25-yr flood flows, and mean monthly flows) for the 2020s and 2050s climate scenarios are presented in Tables 5.3 and 5.4, respectively. The forecasted changes in mean monthly flows for the 2020s and 2050s scenarios are presented graphically in Figure 5.2 and Figure 5.3, respectively. The changes in Figure 5.2 and Figure 5.3 are shown in terms of both percent changes and absolute flows.

Tables 5.3 and 5.4 indicate that the hydrologic effects of forecasted changes in climate vary both spatially across the Athabasca River Basin and temporally during the year. General conclusions from the summary statistics are as follows:

- All the five climate scenarios for the 2020s tend to result in lower mean annual flows, with the decrease in mean annual flow becoming more severe downstream along the Athabasca River. Among the five scenarios, the CCSRNIES-A1F1 scenario predicts the largest decrease, ranging from -8% near Jasper to -16% near Fort McMurray. For the Beaver River Basin, the CCSRNIES-A1F1 scenario predicts a decrease in mean annual flow of almost 22%. The hydrologic response to the effects forecasted by the CCSRNIES-A1F1 scenario appears to be consistent with its "warmer and drier than median conditions" classification by Barlow and Yu (2005). The HADCM3-A2A scenario predicts the smallest decrease, ranging from -2% near Jasper to -5% near Athabasca and -2% near Fort McMurray. For the Beaver River Basin, the HADCM3-A2A scenario predicts no change in mean annual flow. The hydrologic response to the effects forecasted by the HADCM3-A2A scenario appears to be somewhat consistent with its "warmer and wetter than median conditions" classification by Barlow and Yu (2005).

- Changes in mean monthly flows for the 2020s scenarios tend to be positive (increase relative to baseline values) during the spring months and significantly negative (decrease) during the summer months. The seasonal differences in flows are consistent with the relative effects of increased precipitation (more spring runoff) and increased temperatures during the summer months (higher summer evapotranspiration). The differences in monthly hydrologic responses between the 2020s climate scenarios tend to be more distinct in the upper of the Athabasca River Basin, and less so near Fort McMurray. It appears that differences in timing of runoff from the headwaters to the foothills sub-basins tend to dampen the effects on climate change in the lower reaches of the Athabasca River.

- The 2050s climate scenarios result in changes in mean annual flow that are generally more severe compared to the 2020s scenarios, which is consistent with the changes in temperature and precipitation shown in Table 5.1. Among the five scenarios, the CCSRNIES-A1F1 2050s scenario predicts the greatest decrease in mean annual flows, ranging from -16% near Jasper to -21% near Fort McMurray. However, for the Beaver River Basin, the CCSRNIES-A1F1 2050s scenario predicts a decrease in mean annual flow of 9% compared to a decrease of 22% for the 2020s scenario. The 2050s CCSRNIES-A1F1 scenario predicts a higher increase in precipitation in the Beaver River Basin compared to the Athabasca River Basin. The HADCM3-B2B, among the five selected scenarios, tends to represent the median changes in hydrologic responses, which is consistent with its classification by Barlow and Yu (2005).

Table 5.3 Hydrologic Effects of Forecasted Climate Change on Athabasca River and Beaver River Flows - 2020s Scenarios

	Athabasca River near Jasper WSC 07AA002					
	Baseline Flows	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Statistic	(1961-1990)	Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	96.4	-8%	-7%	-2%	-3%	-5%
Mean Open-Water Flow (m^3/s)	154	-8%	-6%	-2%	-3%	-6%
2-Year Peak Flow (m^3/s)	366	-3%	-2%	1%	1%	-3%
10-Year Peak Flow (m^3/s)	416	-4%	-4%	-1%	-1%	-4%
25-Year Peak Flow (m^3/s)	434	-4%	-5%	-2%	-1%	-4%
Mean Monthly Flows (m^3/s)						
Jan	13.6	-6%	-6%	-2%	-4%	-2%
Feb	11.9	-8%	-8%	-5%	-8%	-3%
Mar	10.5	-7%	-6%	-5%	-8%	-2%
Apr	16.3	7%	10%	-17%	-14%	10%
May	75.1	9%	14%	-1%	4%	15%
Jun	230	-4%	2%	2%	6%	2%
Jul	295	-8%	-5%	0%	-1%	-7%
Aug	273	-14%	-17%	-8%	-12%	-14%
Sep	138.6	-18%	-15%	-2%	-6%	-12%
Oct	48.2	-11%	-9%	-3%	-7%	-2%
Nov	26.3	-8%	-7%	-2%	-6%	-2%
Dec	18.4	-7%	-6%	-2%	-5%	-2%

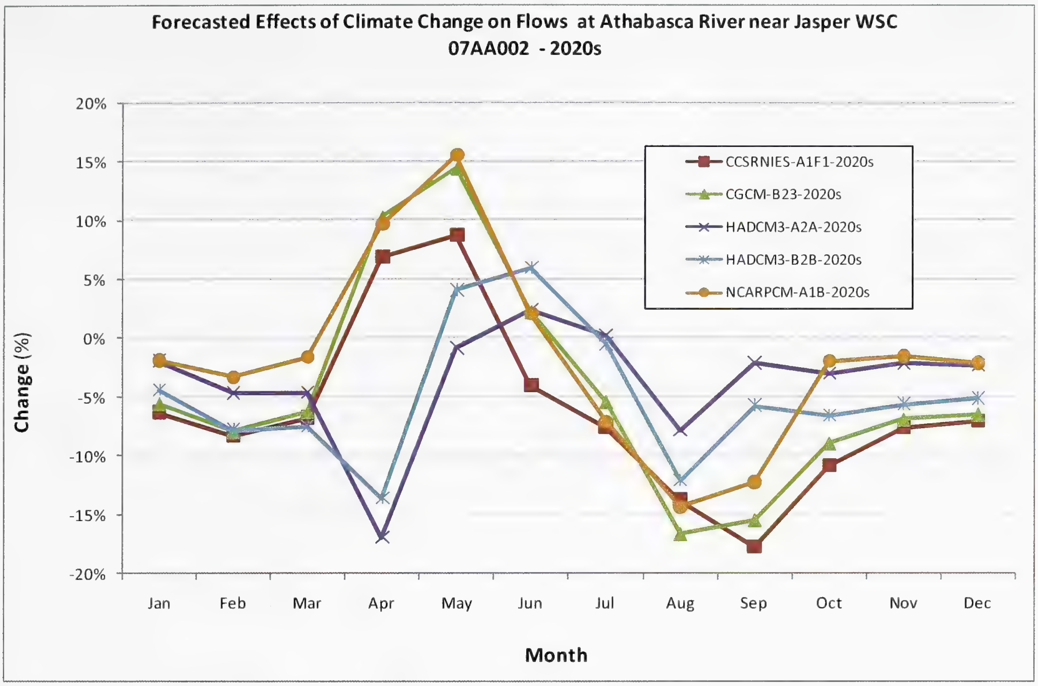
	Athabasca River near Windfall WSC 07AE001					
	Baseline Flows	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Statistic	(1961-1990)	Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	253	-11%	-8%	-4%	-5%	-7%
Mean Open-Water Flow (m^3/s)	400	-12%	-9%	-4%	-5%	-7%
2-Year Peak Flow (m^3/s)	1355	-14%	-9%	-2%	-2%	-9%
10-Year Peak Flow (m^3/s)	1938	-9%	-4%	0%	-2%	-10%
25-Year Peak Flow (m^3/s)	2196	-8%	-2%	1%	-3%	-12%
Mean Monthly Flows (m^3/s)						
Jan	35.8	-8%	-5%	-3%	-5%	-2%
Feb	38.5	-5%	-3%	-8%	-8%	-2%
Mar	51.5	11%	7%	-7%	-6%	-3%
Apr	126	-12%	-11%	-8%	-5%	-5%
May	245	-4%	2%	-3%	1%	6%
Jun	614	-9%	-1%	1%	6%	-1%
Jul	789	-12%	-7%	-2%	-4%	-12%
Aug	602	-16%	-18%	-10%	-15%	-15%
Sep	302	-17%	-17%	-6%	-10%	-8%
Oct	122	-12%	-11%	-7%	-10%	2%
Nov	64.2	-9%	-7%	-4%	-7%	1%
Dec	46.0	-9%	-6%	-4%	-5%	-1%

	Athabasca River at Athabasca WSC 07BE001					
	Baseline Flows	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Statistic	(1961-1990)	Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	463	-16%	-10%	-5%	-6%	-9%
Mean Open-Water Flow (m^3/s)	702	-17%	-10%	-5%	-6%	-10%
2-Year Peak Flow (m^3/s)	1739	-19%	-7%	-3%	-4%	-14%
10-Year Peak Flow (m^3/s)	2712	-15%	-2%	-4%	-7%	-17%
25-Year Peak Flow (m^3/s)	3256	-11%	2%	-4%	-9%	-17%
Mean Monthly Flows (m^3/s)						
Jan	107.7	-16%	-8%	-5%	-4%	-4%
Feb	99.9	-15%	-6%	-7%	-5%	-4%
Mar	131.5	-6%	4%	-7%	-2%	-5%
Apr	402	-9%	-12%	-6%	-2%	-7%
May	565	-15%	-12%	-1%	4%	-4%
Jun	936	-17%	-4%	1%	7%	-6%
Jul	1260	-17%	-5%	-4%	-6%	-16%
Aug	925	-19%	-16%	-11%	-18%	-17%
Sep	539	-19%	-18%	-8%	-14%	-4%
Oct	287	-14%	-12%	-11%	-11%	5%
Nov	176	-14%	-10%	-8%	-6%	1%
Dec	133	-16%	-9%	-6%	-4%	-2%

	Athabasca River below McMurray WSC 07DA001					
	Baseline Flows	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Statistic	(1961-1990)	Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	693	-15%	-9%	-2%	-2%	-6%
Mean Open-Water Flow (m^3/s)	1039	-16%	-10%	-2%	-2%	-7%
2-Year Peak Flow (m^3/s)	2228	-17%	-6%	2%	-1%	-10%
10-Year Peak Flow (m^3/s)	3377	-18%	-3%	4%	0%	-9%
25-Year Peak Flow (m^3/s)	4004	-19%	-2%	5%	2%	-8%
Mean Monthly Flows (m^3/s)						
Jan	177	-12%	-5%	-3%	-1%	-1%
Feb	156	-12%	-4%	-4%	-2%	-1%
Mar	177	-8%	4%	-5%	-1%	-1%
Apr	619	1%	-6%	-7%	0%	-2%
May	1150	-12%	-16%	1%	2%	-4%
Jun	1297	-17%	-6%	3%	7%	-5%
Jul	1627	-19%	-4%	1%	-2%	-15%
Aug	1228	-21%	-15%	-6%	-14%	-16%
Sep	846	-20%	-16%	-6%	-8%	1%
Oct	504	-12%	-8%	-9%	-4%	10%
Nov	314	-11%	-5%	-5%	-2%	6%
Dec	223	-12%	-5%	-3%	-1%	2%

	Beaver River at Cold Lake Reserve WSC 06AD006					
	Baseline Flows	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Statistic	(1961-1990)	Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	23.6	-22%	-5%	0%	-6%	-7%
Mean Open-Water Flow (m^3/s)	35.1	-22%	-5%	1%	-5%	-8%
2-Year Peak Flow (m^3/s)	96.7	-19%	-16%	8%	-3%	3%
10-Year Peak Flow (m^3/s)	269	-22%	12%	17%	10%	-10%
25-Year Peak Flow (m^3/s)	395	-25%	27%	20%	15%	-17%
Mean Monthly Flows (m^3/s)						
Jan	6.40	-23%	-5%	-5%	-11%	-3%
Feb	5.36	-26%	-5%	-3%	-10%	-5%
Mar	6.66	-24%	6%	1%	-6%	2%
Apr	44.3	-3%	-4%	11%	5%	3%
May	57.6	-23%	-26%	6%	-3%	-9%
Jun	40.5	-25%	0%	3%	8%	-15%
Jul	39.4	-30%	19%	4%	4%	-22%
Aug	22.4	-30%	-2%	-2%	-22%	-23%
Sep	23.5	-29%	-14%	-15%	-30%	5%
Oct	18.0	-24%	-1%	-25%	-25%	13%
Nov	10.8	-22%	-4%	-17%	-18%	3%
Dec	7.90	-21%	-4%	-9%	-12%	-3%

Figure 5.3 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2020s Scenarios



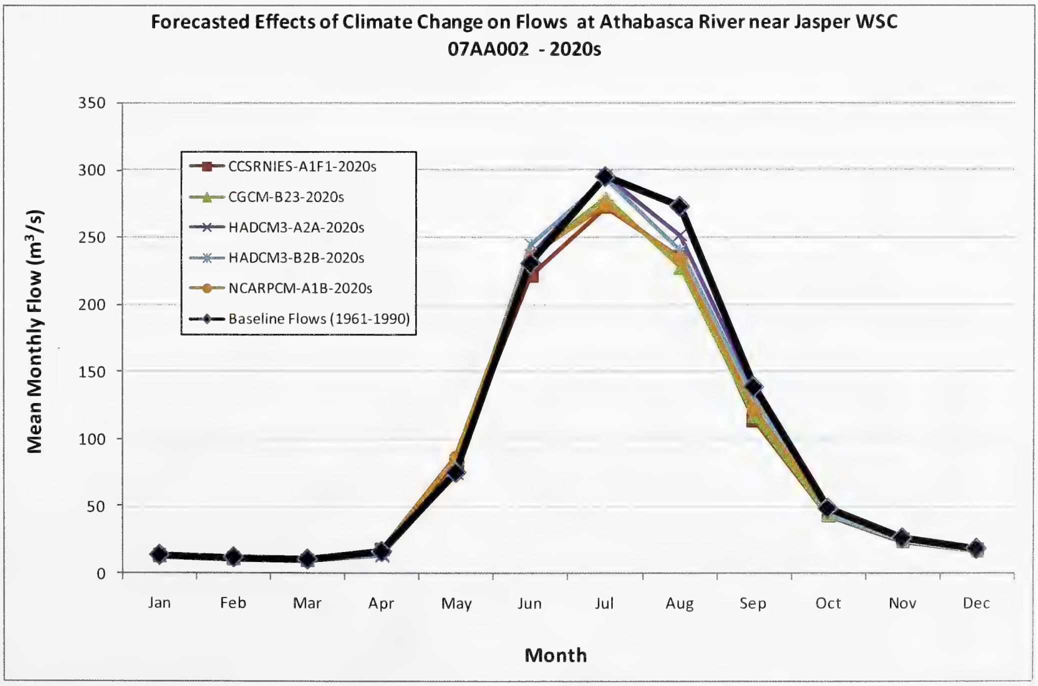
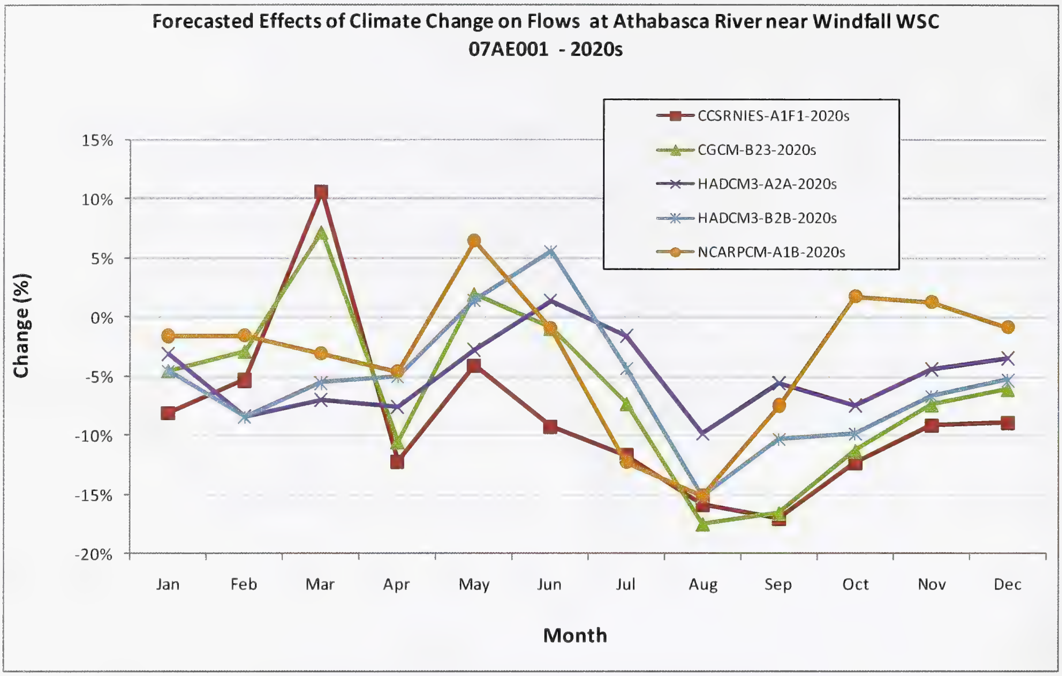


Figure 5.3 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2020s Scenarios (continued)



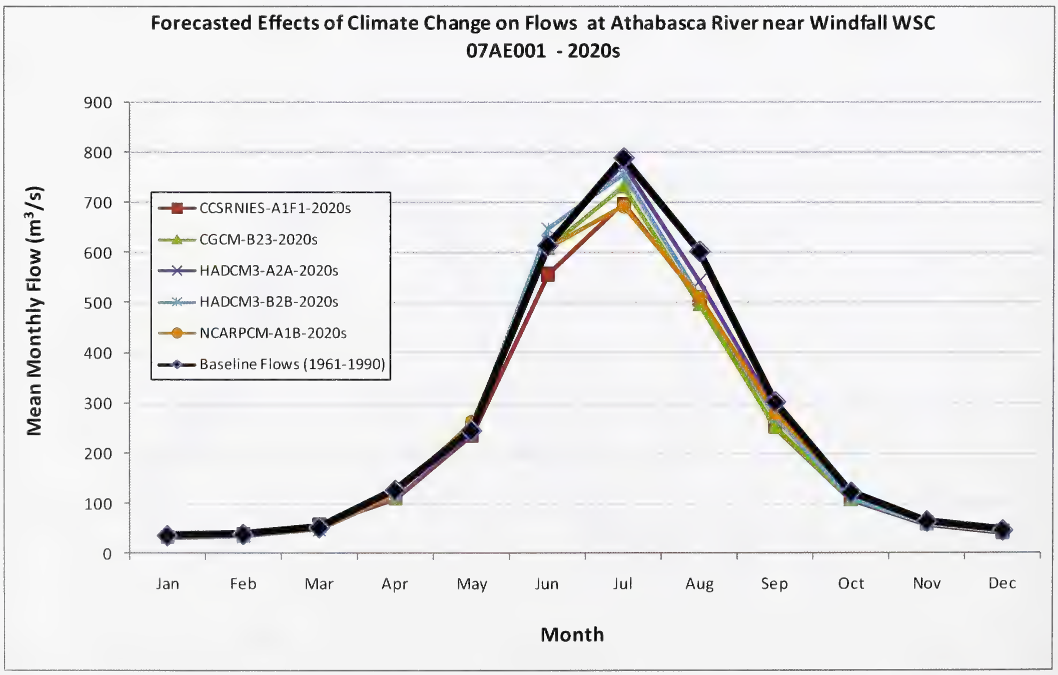
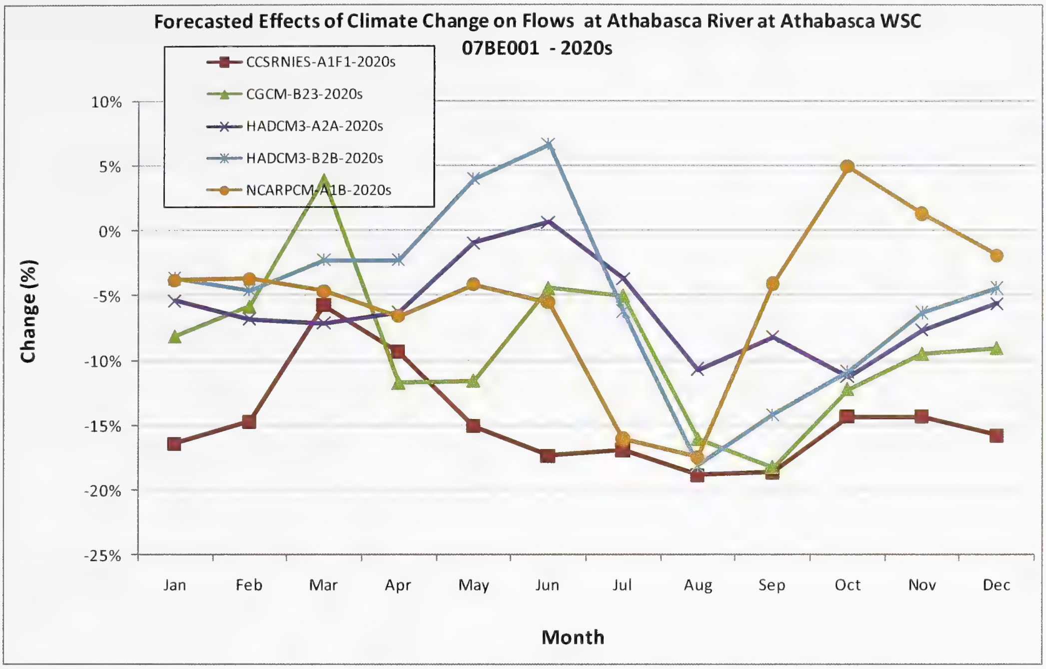


Figure 5.3 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2020s Scenarios (continued)



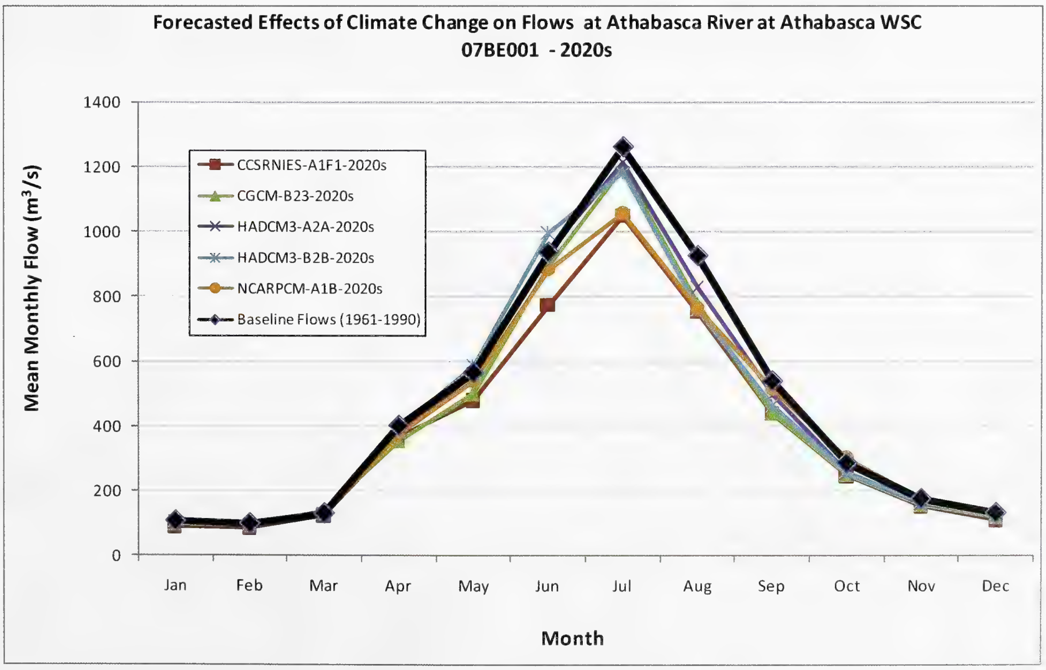
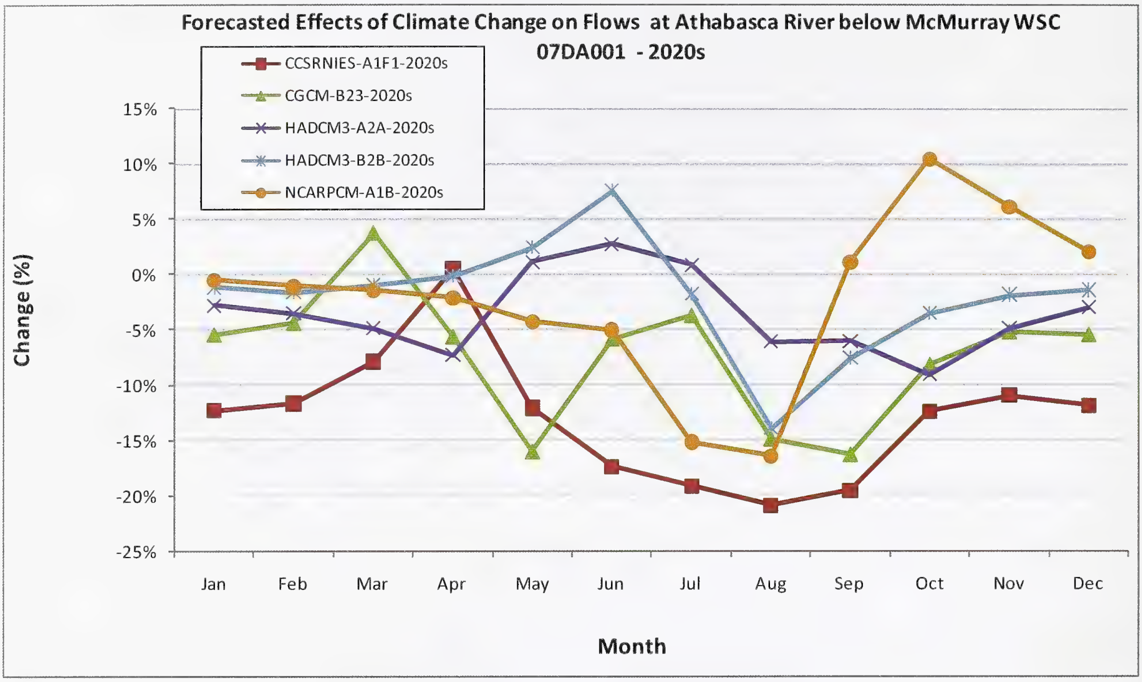


Figure 5.3 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2020s Scenarios (continued)



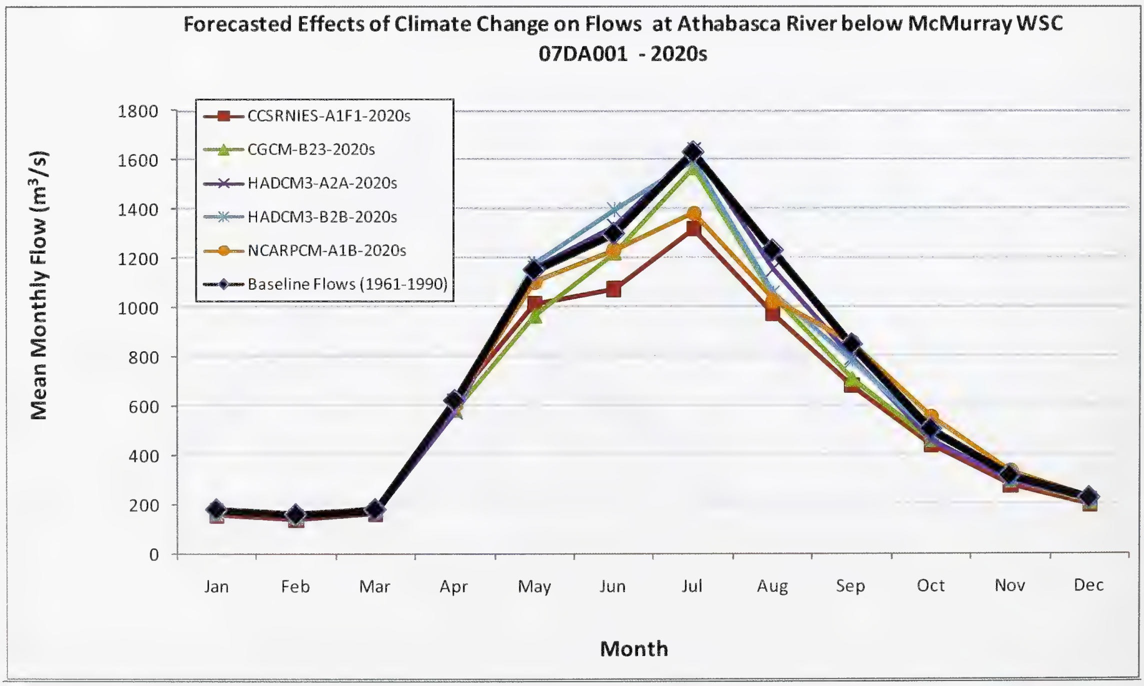


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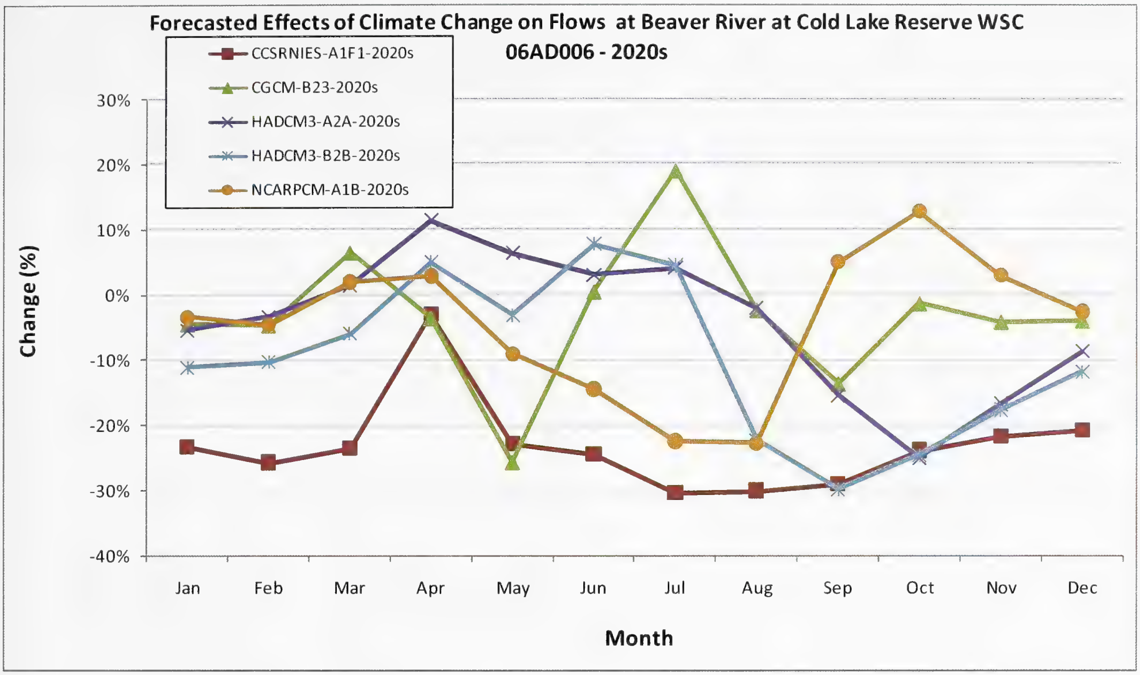
Figure 5.3 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2020s Scenarios (continued)



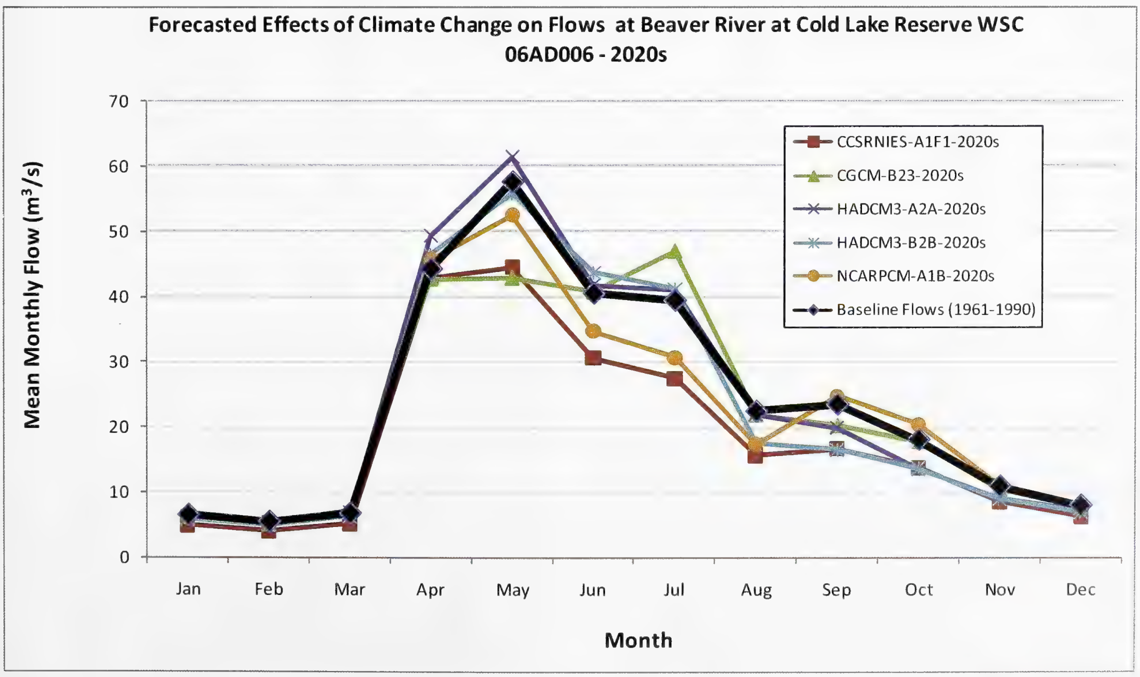


Table 5.4 Hydrologic Effects of Forecasted Climate Change on Athabasca River and Beaver River Flows – 2050s Scenarios

Statistic	Athabasca River near Jasper WSC 07AA002					
	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
Mean Annual Flow (m^3/s)	96.4	-16%	-8%	-8%	-4%	1%
Mean Open-Water Flow (m^3/s)	154	-17%	-8%	-8%	-4%	1%
2-Year Peak Flow (m^3/s)	366	-7%	-4%	-1%	1%	0%
10-Year Peak Flow (m^3/s)	416	-6%	-4%	-2%	0%	0%
25-Year Peak Flow (m^3/s)	434	-6%	-5%	-2%	0%	0%
Mean Monthly Flows (m^3/s)						
Jan	13.6	-10%	-7%	-7%	-5%	2%
Feb	11.9	-14%	-10%	-13%	-10%	-2%
Mar	10.5	-7%	-8%	-12%	-10%	-1%
Apr	16.3	59%	7%	-20%	-16%	8%
May	75.1	28%	26%	13%	4%	23%
Jun	230	2%	7%	9%	9%	9%
Jul	295	-19%	-9%	-7%	-2%	-2%
Aug	273	-39%	-25%	-26%	-18%	-11%
Sep	138.6	-32%	-17%	-14%	-4%	1%
Oct	48.2	-13%	-9%	-6%	-2%	6%
Nov	26.3	-10%	-8%	-8%	-5%	4%
Dec	18.4	-11%	-8%	-8%	-5%	2%

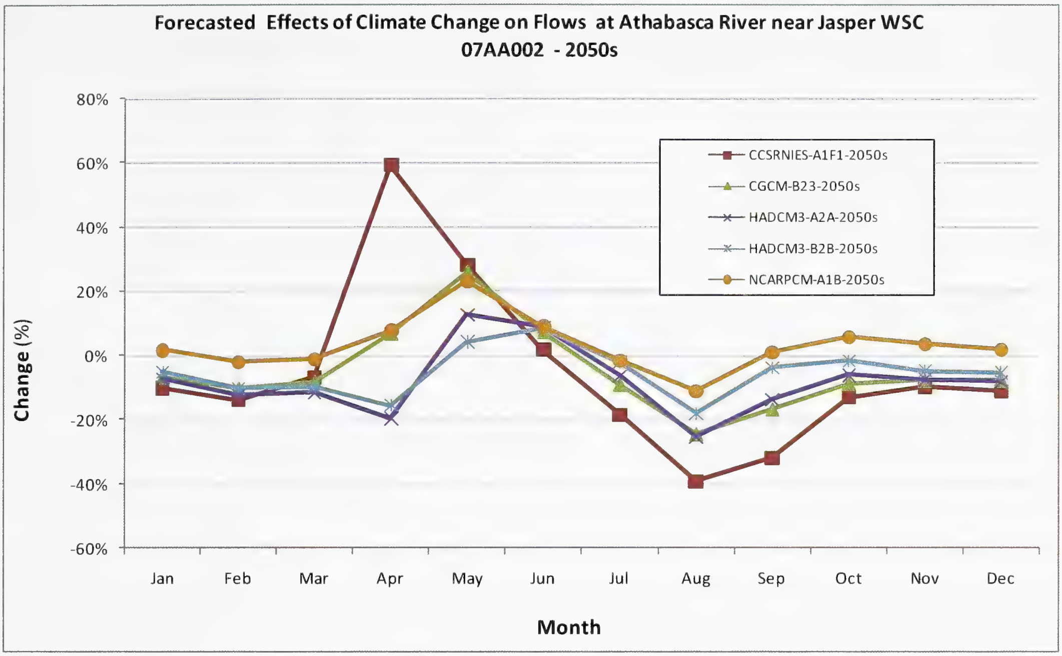
Statistic	Athabasca River near Windfall WSC 07AE001					
	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
Mean Annual Flow (m^3/s)	253	-19%	-11%	-12%	-8%	-1%
Mean Open-Water Flow (m^3/s)	400	-20%	-11%	-12%	-8%	-1%
2-Year Peak Flow (m^3/s)	1355	-28%	-16%	-10%	-4%	-3%
10-Year Peak Flow (m^3/s)	1938	-13%	-8%	-5%	-1%	1%
25-Year Peak Flow (m^3/s)	2196	-3%	-3%	-3%	-1%	2%
Mean Monthly Flows (m^3/s)						
Jan	35.8	-11%	-7%	-10%	-6%	2%
Feb	38.5	-15%	-6%	-21%	-13%	2%
Mar	51.5	-4%	2%	-21%	-7%	-1%
Apr	126	-4%	-17%	-13%	-12%	-8%
May	245	4%	8%	2%	-5%	8%
Jun	614	-6%	2%	3%	5%	6%
Jul	789	-23%	-14%	-12%	-8%	-3%
Aug	602	-37%	-25%	-27%	-20%	-11%
Sep	302	-31%	-18%	-19%	-10%	1%
Oct	122	-18%	-12%	-14%	-9%	5%
Nov	64.2	-13%	-10%	-11%	-6%	3%
Dec	46.0	-13%	-9%	-11%	-7%	1%

Statistic	Athabasca River at Athabasca WSC 07BE001					
	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
Mean Annual Flow (m^3/s)	463	-21%	-15%	-12%	-10%	-4%
Mean Open-Water Flow (m^3/s)	702	-22%	-15%	-12%	-10%	-5%
2-Year Peak Flow (m^3/s)	1739	-22%	-15%	-10%	-9%	-7%
10-Year Peak Flow (m^3/s)	2712	-11%	-7%	-10%	-10%	-3%
25-Year Peak Flow (m^3/s)	3256	-3%	-2%	-10%	-10%	1%
Mean Monthly Flows (m^3/s)						
Jan	107.7	-18%	-16%	-10%	-7%	-2%
Feb	99.9	-17%	-13%	-14%	-8%	0%
Mar	131.5	-11%	-5%	-19%	-4%	-1%
Apr	402	-20%	-19%	-12%	-9%	-8%
May	565	-15%	-12%	1%	-3%	-3%
Jun	936	-12%	-5%	1%	2%	0%
Jul	1260	-19%	-12%	-12%	-12%	-7%
Aug	925	-34%	-24%	-27%	-23%	-10%
Sep	539	-32%	-22%	-20%	-14%	1%
Oct	287	-22%	-16%	-14%	-10%	3%
Nov	176	-19%	-16%	-13%	-8%	0%
Dec	133	-19%	-16%	-11%	-7%	-1%

Statistic	Athabasca River below McMurray WSC 07DA001					
	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
Mean Annual Flow (m^3/s)	693	-21%	-17%	-8%	-6%	-4%
Mean Open-Water Flow (m^3/s)	1039	-22%	-17%	-7%	-6%	-5%
2-Year Peak Flow (m^3/s)	2228	-20%	-16%	-1%	-5%	-6%
10-Year Peak Flow (m^3/s)	3377	-15%	-11%	2%	-4%	-3%
25-Year Peak Flow (m^3/s)	4004	-11%	-9%	3%	-3%	-1%
Mean Monthly Flows (m^3/s)						
Jan	177	-14%	-13%	-7%	-3%	0%
Feb	156	-13%	-12%	-8%	-4%	1%
Mar	177	-9%	-5%	-14%	-2%	1%
Apr	619	-17%	-15%	-12%	-4%	-2%
May	1150	-22%	-21%	4%	-1%	-3%
Jun	1297	-15%	-11%	4%	2%	-3%
Jul	1627	-18%	-14%	-4%	-9%	-10%
Aug	1228	-31%	-24%	-21%	-21%	-12%
Sep	846	-29%	-22%	-18%	-8%	1%
Oct	504	-18%	-17%	-13%	0%	7%
Nov	314	-14%	-14%	-9%	-1%	4%
Dec	223	-14%	-14%	-8%	-2%	1%

Statistic	Beaver River at Cold Lake Reserve WSC 06AD006					
	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
Mean Annual Flow (m^3/s)	23.6	-9%	-19%	-2%	-10%	-14%
Mean Open-Water Flow (m^3/s)	35.1	-9%	-19%	0%	-10%	-14%
2-Year Peak Flow (m^3/s)	96.7	-7%	-21%	12%	-7%	-1%
10-Year Peak Flow (m^3/s)	269	-3%	-8%	24%	4%	-11%
25-Year Peak Flow (m^3/s)	395	-3%	-4%	28%	7%	-16%
Mean Monthly Flows (m^3/s)						
Jan	6.40	-10%	-18%	-9%	-13%	-14%
Feb	5.36	-10%	-19%	-7%	-12%	-14%
Mar	6.66	0%	-5%	-3%	4%	4%
Apr	44.3	5%	-5%	18%	8%	4%
May	57.6	-8%	-30%	7%	-11%	-15%
Jun	40.5	-7%	-16%	0%	-7%	-16%
Jul	39.4	-9%	-13%	6%	-10%	-24%
Aug	22.4	-16%	-26%	-15%	-27%	-24%
Sep	23.5	-24%	-27%	-28%	-22%	-13%
Oct	18.0	-18%	-20%	-30%	-18%	-18%
Nov	10.8	-15%	-20%	-20%	-17%	-17%
Dec	7.90	-10%	-17%	-11%	-13%	-14%

Figure 5.4 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2050s Scenarios



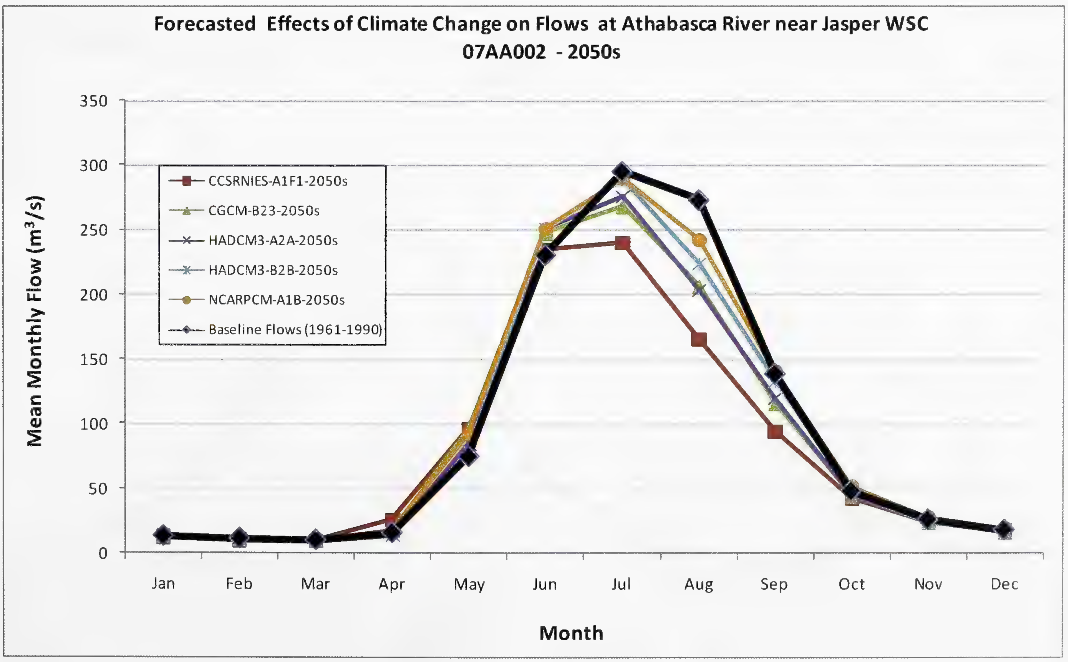
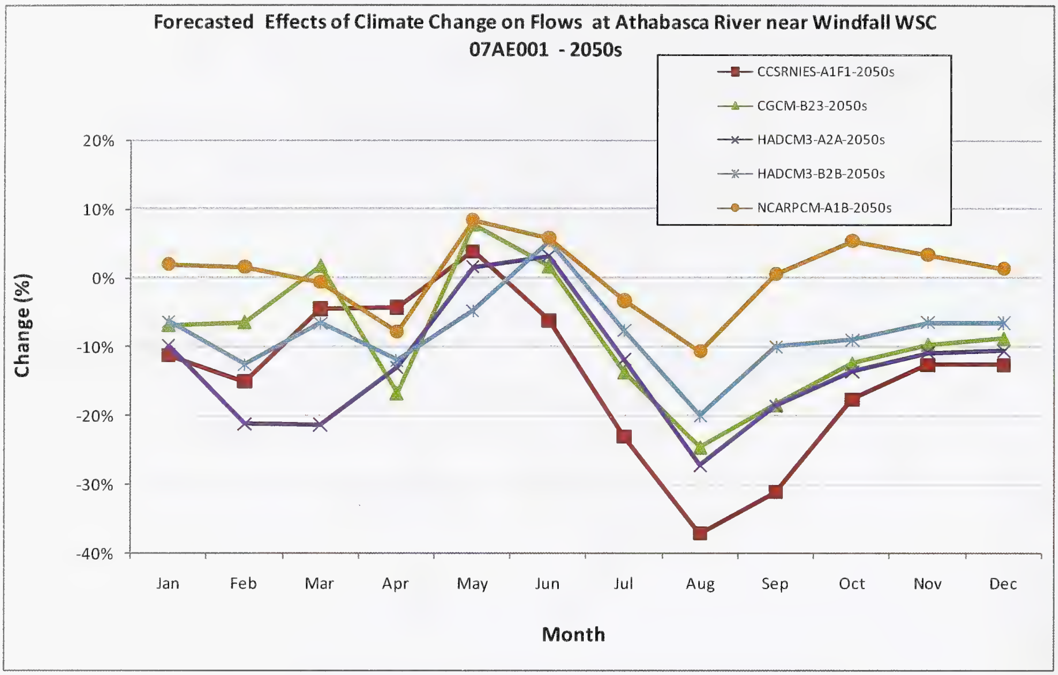


Figure 5.4 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2050s Scenarios (continued)



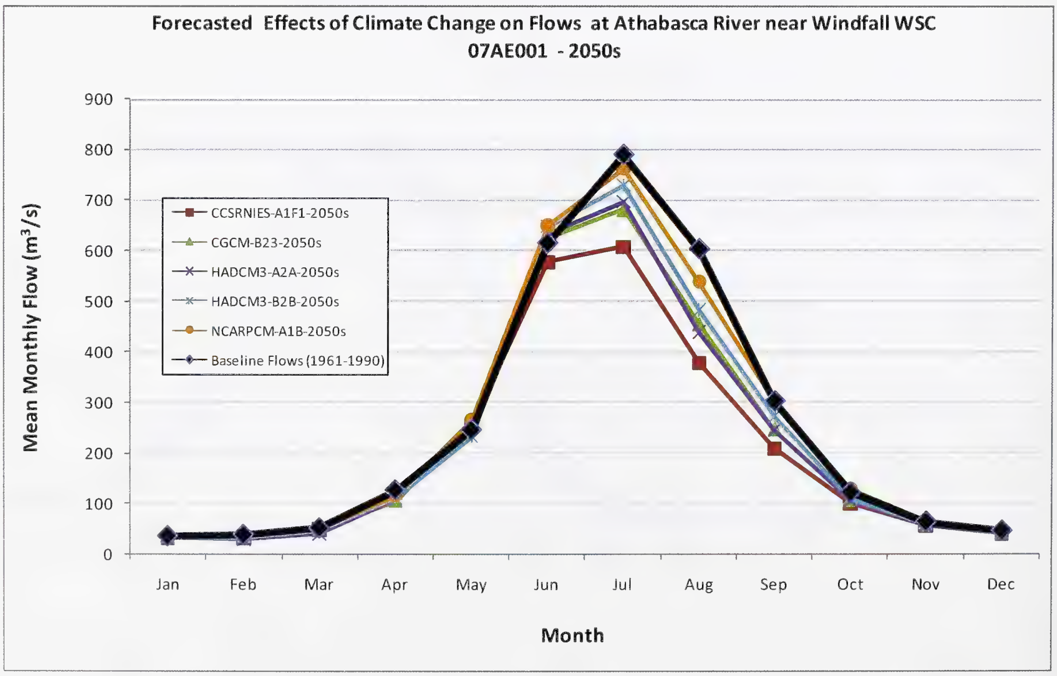
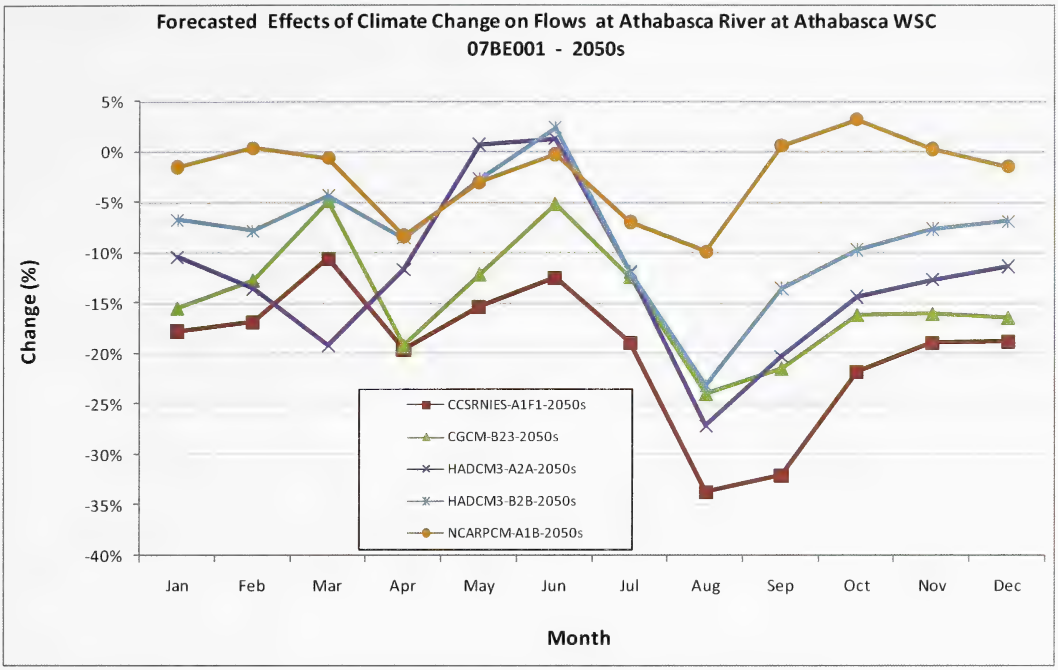


Figure 5.4 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2050s Scenarios (continued)



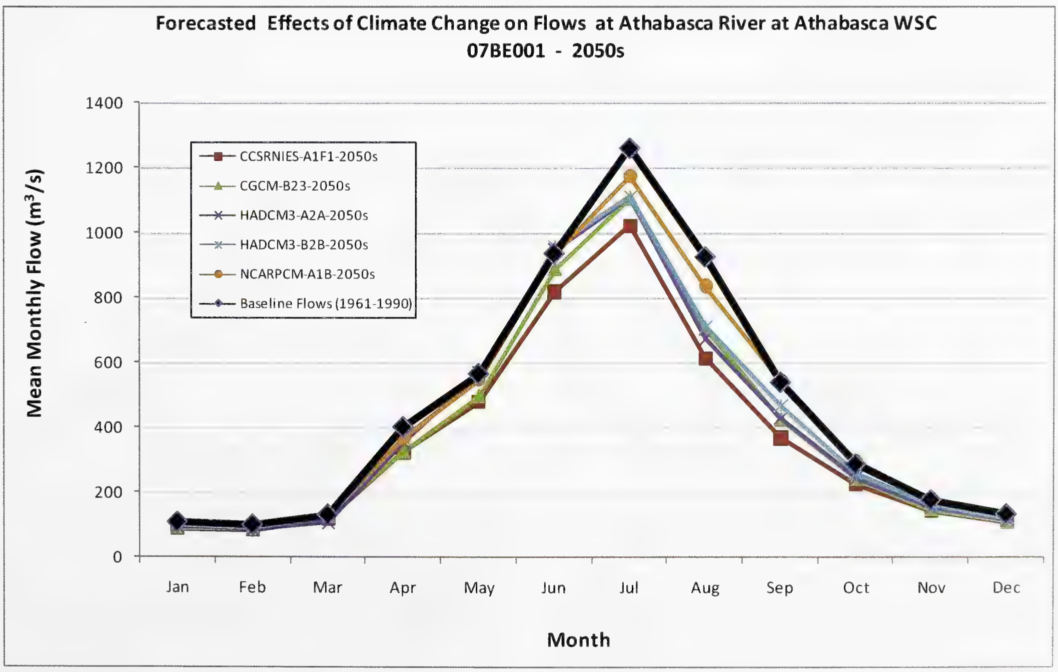
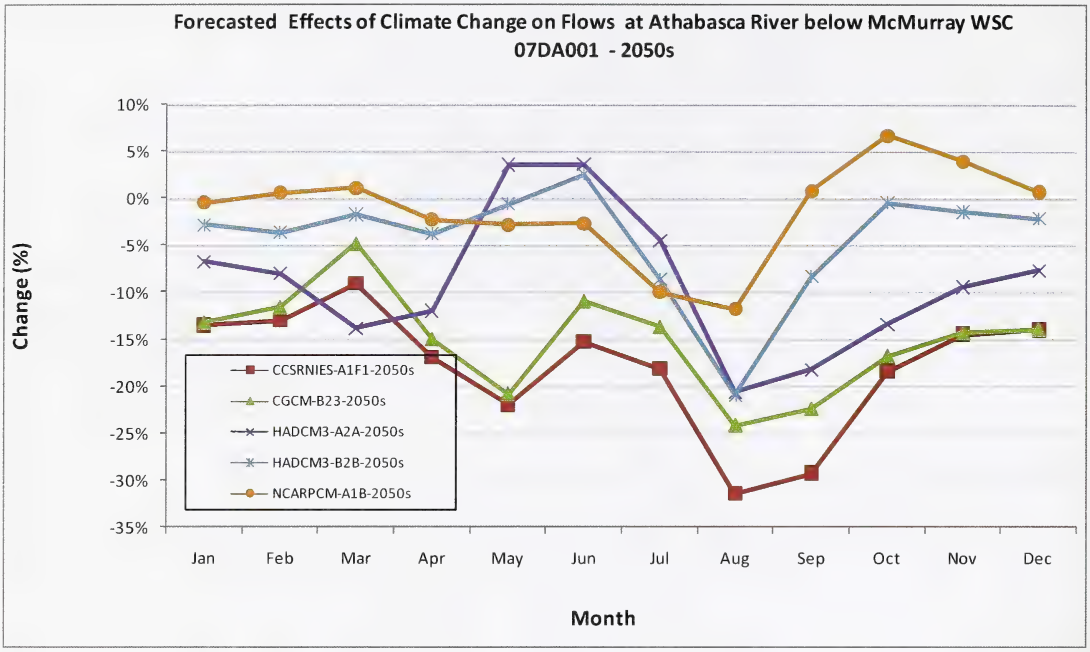


Figure 5.4 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2050s Scenarios (continued)



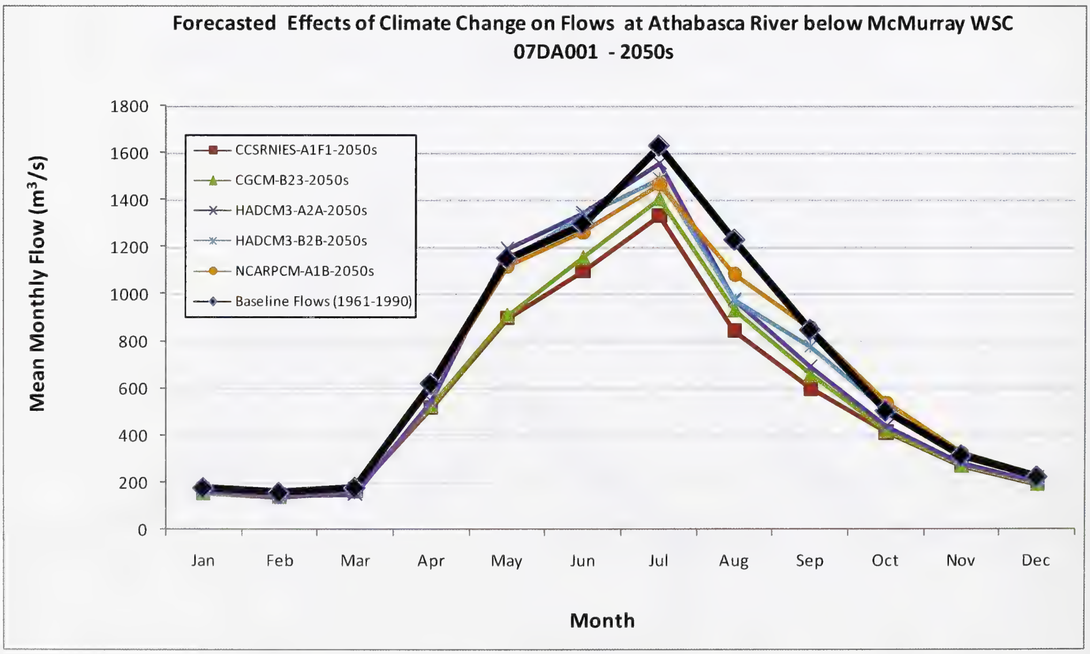
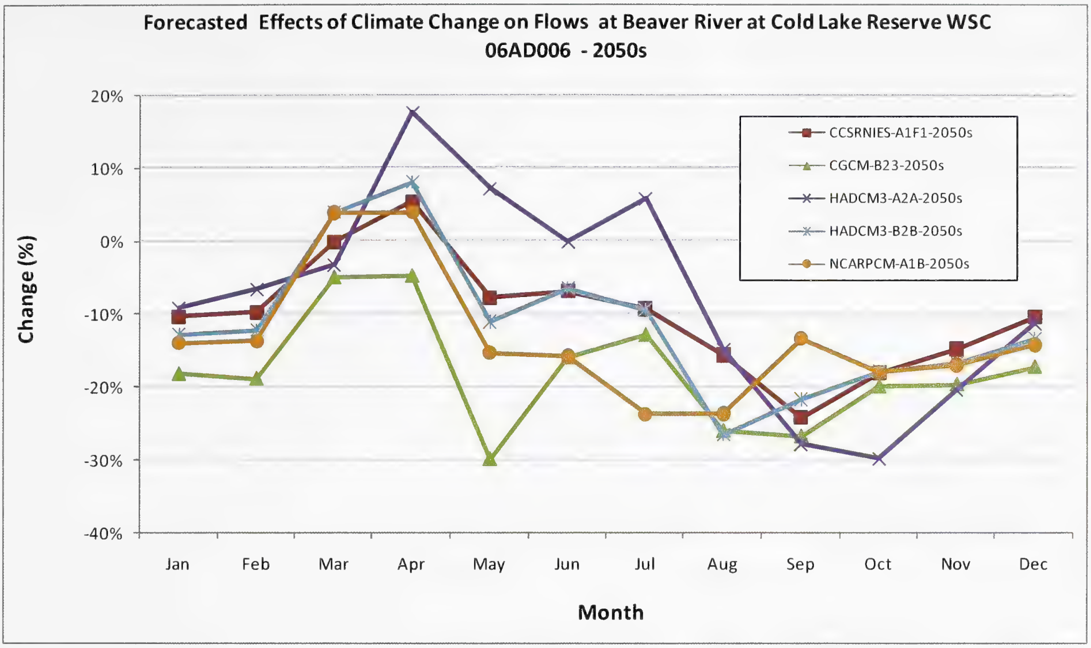
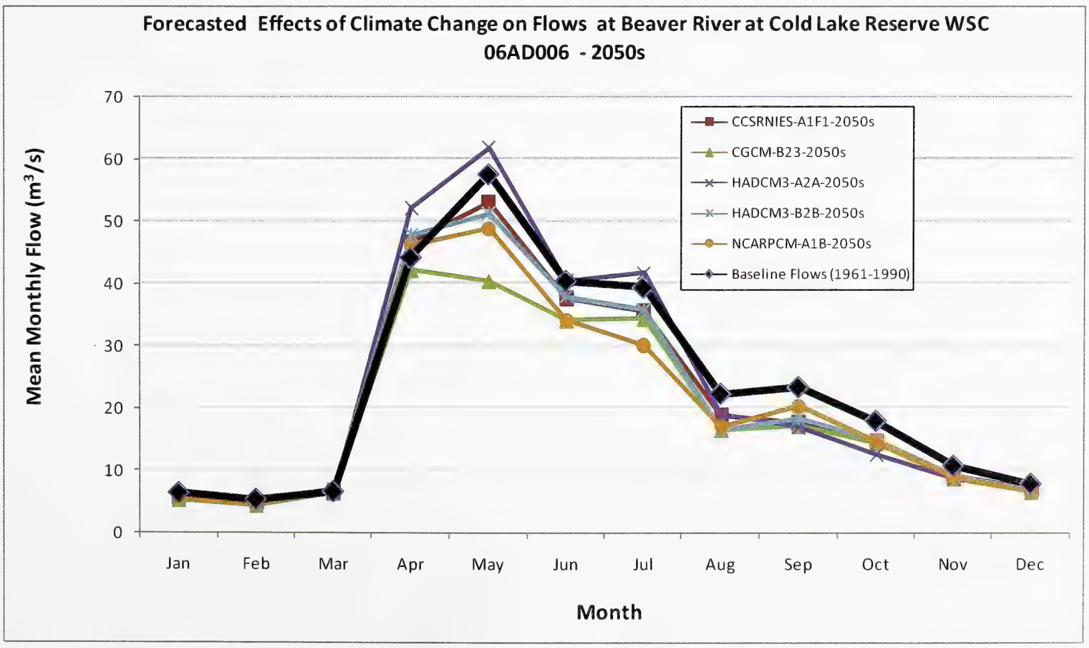


Figure 5.4 Forecasted Effects of Climate Change on Simulated Mean Monthly Flows – 2050s Scenarios (continued)





- Changes in mean monthly flows for the 2050s scenarios tend to mimic the 2020s results.

- The range of effects of future climate regimes on flows in the Lower Athabasca Regional Plan Area (LARP) is summarized in Table 5.5. Three locations are used for the summary: (1) Athabasca River at Athabasca (07BE001) to represent inflow to the LARP area, (2) Athabasca River below McMurray (07DA001) to represent flows in the oil sands region where the amount of water withdrawal is a key consideration in the planning process, and (3) Beaver River at Cold Lake Reserve sub-basin (06AD006) to represent the southern portion of the LARP area. The statistics selected are (1) mean annual flow to represent annual yield, (2) mean August flow to represent summer low flows, (3) mean February flow to represent winter low flows, (4) mean June flow for Athabasca River and mean April flow for Beaver River to represent spring flood flows, and (5) 10-year flood flow to represent annual floods. For each of the five statistics, Table 5.5 shows the scenario resulting in the maximum decrease, maximum increase/least decrease and average change.

  The summary results indicate that water yield from the two basins will generally decrease, with the effects (in percentage terms) more significant during the month of August. The effects on low February flows, although reduced, tend to be less (in percentage terms) compared to changes in August flows. Flood flows tend to be higher under the future climate scenarios. Table 5.5 summarizes the effects of the simulated climate scenarios on the 10-year 7-day and 30-day winter low flows on the Athabasca River at Athabasca, Athabasca River below McMurray and on the Beaver River at Cold Lake. Tables 5.6, 5.7 and 5.8 provide the winter low flow statistics at these three locations, respectively. The effects appear to be very similar to those on the mean February flows for the Athabasca River below Fort McMurray. On the Beaver River, the effects of the climate scenarios tend to be more severe on the 7-day and 30-day lows than on the mean February flows. As expected, on a large basin, such as the Athabasca River at Fort McMurray, the variability in winter low flows tend to be much less than on the relatively smaller basins such as the Beaver River Basin. While the results on the flood and low flows are useful, it should be noted that they are based on the simulation of climate change characterized by predicted changes in mean monthly temperature and precipitation. The climate changes do not reflect changes that may occur for shorter durations down to the daily scale (scale at which extreme events occur), which may influence the future variability in the low and flood flow series. Section 5.4 discusses the effect of climate change on variability.

Table 5.5 Range of Potential Future Climate Effects on Flows in the Lower Athabasca Region

Flow Statistic	Athabasca River at Athabasca Range of Change in Flow (%)			Athabasca River at McMurray Range of Change in Flow (%)			Beaver River at Cold Lake Range of Change in Flow (%)		
2020s	**Low**	**High**	**Median**	**Low**	**High**	**Median**	**Low**	**High**	**Median**
Mean Annual Flow	-16%	-5%	-9%	-15%	-2%	-6%	-22%	0%	-7%
Scenario	C1	H1	N	C1	H2	N	C1	H1	N
Mean August Flow	-19%	-11%	-16%	-21%	-6%	-14%	-30%	-2%	-22%
Scenario	C1	H1	C2	C1	H1	H2	C1	H1	H2
Mean February Flow	-15%	-4%	-7%	-12%	-1%	-4%	-26%	-3%	-10%
Scenario	C1	N	H1	C1	N	C2	C1	H1	H2
Mean June or April Flow	-17%	7%	-4%	-17%	7%	-5%	-4%	11%	3%
Scenario	C1	H2	C2	C1	H2	N	C2	H1	N
10-year Flood Flow	-17%	2%	-7%	-18%	4%	-3%	-22%	17%	10%
Scenario	N	C2	H2	C1	H1	C2	C1	H1	H2
10-year 7-day Low Flow	-16%	-1%	-4%	-12%	2%	-3%	-44%	-7%	-20%
Scenario	C1	H2	H1	C1	H2	N	C1	C2	N
10-year 30-day Low Flow	-16%	-1%	-5%	-12%	1%	-3%	-44%	-7%	-20%
Scenario	C1	H2	H1	C1	H2	N	C1	C2	N
2050s	**Low**	**High**	**Median**	**Low**	**High**	**Median**	**Low**	**High**	**Median**
Mean Annual Flow	-21%	-4%	-12%	-21%	-4%	-8%	-19%	-2%	-10%
Scenario	C1	N	H1	C1	N	H2	C2	H1	H2
Mean August Flow	-34%	-10%	-24%	-31%	-12%	-21%	-27%	-15%	-24%
Scenario	C1	N	C2	C1	N	H1	H2	H1	N
Mean February Flow	-17%	0%	-8%	-13%	1%	-8%	-19%	-7%	-12%
Scenario	C1	N	H2	C1	N	H1	C2	H1	H2
Mean June or April Flow	-12%	2%	-5%	-15%	4%	-3%	-5%	18%	5%
Scenario	C1	H2	C2	C1	H1	N	C2	H1	C1
10-year Flood Flow	-11%	-3%	-7%	-15%	-2%	-4%	-11%	24%	-3%
Scenario	C1	N	C2	C1	H1	H2	N	H1	C1
10-year 7-day Low Flow	-21%	-2%	-11%	-15%	-2%	-7%	-39%	-20%	-34%
Scenario	C1	N	H1	C1	N	H1	C2	C1	H2
10-year 30-day Low Flow	-22%	-3%	-11%	-16%	-2%	-8%	-39%	-21%	-34%
Scenario	C1	N	H1	C1	N	H1	C2	C1	H2

Labels for Climate Scenarios

CCSRNIES-A1F1	C1
CGCM-B23	C2
HADCM3-A2A	H1
HADCM3-B2B	H2
NCARPCM-A1B	N

Table 5.6 Effects of Climate Scenarios on Winter Low Flows in the Athabasca River at Athabasca

	Athabasca River at Athabasca WSC 07BE001					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
7Q10-Low Flow (m^3/s)	60.2	50.3	54.8	57.6	59.8	57.2
30Q10-Low Flow (m^3/s)	63.1	52.8	57.2	60.1	62.3	60.0
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s	CGCM-B23-2050s	HADCM3-A2A-2050s	HADCM3-B2B-2050s	NCARPCM-A1B-2050s
7Q10-Low Flow (m^3/s)	60.2	47.8	49.8	53.6	56.7	58.9
30Q10-Low Flow (m^3/s)	63.1	49.3	51.7	55.6	59.1	61.4

	Athabasca River at Athabasca WSC 07BE001					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s Change (%)	CGCM-B23-2020s Change (%)	HADCM3-A2A-2020s Change (%)	HADCM3-B2B-2020s Change (%)	NCARPCM-A1B-2020s Change (%)
7Q10-Low Flow (m^3/s)	60.2	-16%	-8.8%	-4.2%	-0.6%	-5.0%
30Q10-Low Flow (m^3/s)	63.1	-16%	-9.4%	-4.7%	-1.2%	-4.9%
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
7Q10-Low Flow (m^3/s)	60.2	-21%	-17%	-10.8%	-5.7%	-2.1%
30Q10-Low Flow (m^3/s)	63.1	-22%	-18%	-11.9%	-6.4%	-2.7%

NOTES:
7Q10 = 10-year 7-day winter low flow (November/15 ~ April/14)
30Q10 = 10-year 30-day winter low flow (November/15 ~ April/14)

Table 5.7 Effects of Climate Scenarios on Winter Low Flows in the Athabasca River at Fort McMurray

	Athabasca River below McMurray WSC 07DA001					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
7Q10-Low Flow (m^3/s)	107	94.0	101	105	109	104
30Q10-Low Flow (m^3/s)	110	96.7	104	108	112	107
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s	CGCM-B23-2050s	HADCM3-A2A-2050s	HADCM3-B2B-2050s	NCARPCM-A1B-2050s
7Q10-Low Flow (m^3/s)	107	91.0	92.8	99.5	104	105
30Q10-Low Flow (m^3/s)	110	92.8	94.9	102	107	108

	Athabasca River below McMurray WSC 07DA001					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s Change (%)	CGCM-B23-2020s Change (%)	HADCM3-A2A-2020s Change (%)	HADCM3-B2B-2020s Change (%)	NCARPCM-A1B-2020s Change (%)
7Q10-Low Flow (m^3/s)	107	-12%	-5.4%	-1.8%	1.8%	-2.8%
30Q10-Low Flow (m^3/s)	110	-12%	-6.0%	-2.3%	1.2%	-2.7%
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
7Q10-Low Flow (m^3/s)	107	-15%	-13%	-7.2%	-2.6%	-1.6%
30Q10-Low Flow (m^3/s)	110	-16%	-14%	-7.9%	-2.9%	-1.9%

NOTES:
7Q10 = 10-year 7-day winter low flow (November/15 ~ April/14)
30Q10 = 10-year 30-day winter low flow (November/15 ~ April/14)

Table 5.8 Effects of Climate Scenarios on Winter Low Flows in the Beaver River at Cold Lake

Statistic	Beaver River at Cold Lake Reserve WSC 06AD006					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
7Q10-Low Flow (m^3/s)	1.56	0.874	1.45	1.39	1.10	1.24
30Q10-Low Flow (m^3/s)	1.65	0.934	1.53	1.46	1.17	1.32
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s	CGCM-B23-2050s	HADCM3-A2A-2050s	HADCM3-B2B-2050s	NCARPCM-A1B-2050s
7Q10-Low Flow (m^3/s)	1.56	1.24	0.950	1.13	1.03	1.06
30Q10-Low Flow (m^3/s)	1.65	1.31	1.00	1.19	1.09	1.12

Statistic	Beaver River at Cold Lake Reserve WSC 06AD006					
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2020s Change (%)	CGCM-B23-2020s Change (%)	HADCM3-A2A-2020s Change (%)	HADCM3-B2B-2020s Change (%)	NCARPCM-A1B-2020s Change (%)
7Q10-Low Flow (m^3/s)	1.56	-44%	-7.0%	-11%	-29%	-20%
30Q10-Low Flow (m^3/s)	1.65	-44%	-7.2%	-12%	-29%	-20%
Statistic	Baseline Flows (1961-1990)	CCSRNIES-A1F1-2050s Change (%)	CGCM-B23-2050s Change (%)	HADCM3-A2A-2050s Change (%)	HADCM3-B2B-2050s Change (%)	NCARPCM-A1B-2050s Change (%)
7Q10-Low Flow (m^3/s)	1.56	-20%	-39%	-28%	-34%	-32%
30Q10-Low Flow (m^3/s)	1.65	-21%	-39%	-28%	-34%	-32%

NOTES:
7Q10 = 10-year 7-day winter low flow (November/15 ~ April/14)
30Q10 = 10-year 30-day winter low flow (November/15 ~ April/14)

5.3.6 Discussion of Hydrologic Effects of Future Climate Regimes

The results of the assessment of the effects of climate change on flows in the Athabasca River and Beaver River basins tend to be in general agreement with recent studies carried out by independent researchers. Studies on the effects of potential climate change on flows in watersheds in Alberta include those by Kerhoven and Gan (2005) on the Athabasca River Basin (ARB) and Pietroniro and Toth (2006) on the South Saskatchewan River Basin (SSRB). Kerkhoven and Gan (2006) applied the MISBA model to the Athabasca River basin using the ERA-40 re-analysis data of ECMWF (European Centre for Mid-range Weather Forecasts). MISBA is the ISBA (Interactions Soil-Biosphere-Atmosphere developed by Meteo France) model modified to statistically represent sub-grid variability of soil, vegetation and elevation in the Athabasca River Basin. MISBA was used to predict changes to the hydrology of the Athabasca River Basin under conditions predicted by a number of climate scenarios for the 21st century. Although most of the scenarios predicted increased precipitation in the ARB, all the scenarios resulted in significantly decreased stream flows by the end of the century (2070-2099). This was primarily because of a predicted decrease in the size of the winter snow pack due to warmer winters. Warmer winters result in less snow accumulation and increased evaporation. Mean annual flows were predicted to decrease by almost 25% by the last 30 years of the century. The high flow season also became much shorter.

Pietroniro and Toth (2006) present and discuss the results of a study of the water availability in the South Saskatchewan River Basin (SSRB) under climate change scenarios. The objective of the study was to predict the future water availability in the SSRB under the potential impact of climate change using hydrologic models calibrated to SSRB and forced by downscaled climate scenarios projected by some selected GCMs. Down-scaled GCMs were used to project changes in local temperature and precipitation patterns. The climate information was then used to simulate future river flows in the SSRB using the WATFLOOD, SACRAMENTO and MISBA hydrologic models. Flow predictions vary by sub-basin, with general reduction in flows for the modelled sub-basins ranging from -13% to -4%.

The range of effects predicted by the HSPF model for the LARP area is generally consistent with the results of similar studies in Alberta. Depending on the flow statistic, the range of effects can span more than 10%, which reflects the assumptions inherent in the formulation of the climate scenarios as well as uncertainties in the predictions. The IPCC recommends that several climate scenarios need to be considered for assessment of effects because a single climate model scenario does not provide a reliable description of the climatic evolution, while ensembles of state-of-the-art climate models, on the other hand, capture the main features of the past climatic evolution. Given that the total number of combinations of GCMs and scenarios can be excessive, a few combinations of GCMs and scenarios have been selected for this study so that the range of climate scenarios can represent dry, median and wet scenarios, while avoiding excessive runs that may be redundant (Barrow and Yu, 2005). In addition, it is important to determine the time horizon of interest for assessing the effects of climate change. For example, for water supply assessment, the planning period could be 20-30 years as opposed to 100 years. The uncertainty in the predictions of the effects of climate change on water supply in the distant future may be larger than the predicted effects themselves. In any case, there is a greater possibility for adaptation over the long-term as better models become available and predictions become more reliable.

The range of hydrologic effects predicted by the HSPF model for the LARP area reflects the range of conditions that basin planners should consider. Hence, the predicted effects using HSPF and future climate scenarios provide a rational basis for water management and planning purposes in the LARP area.

5.4 Climate Change and Climate Variability

While GCMs predict a progressive increase in mean temperature, a similar incremental change in hydro-climate should not be expected, however, because time series of flows and climate moisture indices are dominated by departures from mean conditions at seasonal to multi-decadal time scales (Sauchyn *et al.* 2008). Sauchyn *et al.* (2008) reports that quasi-periodic cycles dominate the behaviour of Alberta's hydro-climate. Climate variability (i.e., wet and dry cycles) is observed both in the instrumental (1901-2000) and tree-ring (1702-2003) record on inter-annual (2-8 years), inter-decadal (8-20 years) and multi-decadal (20-60 years) scales. The variability has

5.3.6 Discussion of Hydrologic Effects of Future Climate Regimes

The results of the assessment of the effects of climate change on flows in the Athabasca River and Beaver River basins tend to be in general agreement with recent studies carried out by independent researchers. Studies on the effects of potential climate change on flows in watersheds in Alberta include those by Kerhoven and Gan (2005) on the Athabasca River Basin (ARB) and Pietroniro and Toth (2006) on the South Saskatchewan River Basin (SSRB). Kerkhoven and Gan (2006) applied the MISBA model to the Athabasca River basin using the ERA-40 re-analysis data of ECMWF (European Centre for Mid-range Weather Forecasts). MISBA is the ISBA (Interactions Soil-Biosphere-Atmosphere developed by Meteo France) model modified to statistically represent sub-grid variability of soil, vegetation and elevation in the Athabasca River Basin. MISBA was used to predict changes to the hydrology of the Athabasca River Basin under conditions predicted by a number of climate scenarios for the 21st century. Although most of the scenarios predicted increased precipitation in the ARB, all the scenarios resulted in significantly decreased stream flows by the end of the century (2070-2099). This was primarily because of a predicted decrease in the size of the winter snow pack due to warmer winters. Warmer winters result in less snow accumulation and increased evaporation. Mean annual flows were predicted to decrease by almost 25% by the last 30 years of the century. The high flow season also became much shorter.

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been linked to sea surface temperature (SST) anomalies in the tropical and extra-tropical regions of the Pacific Ocean, ENSO and PDO, respectively.

The Prairies have Canada's most variable hydro-climate, and the wet and dry cycles have significant implications for prairie communities and economies and the management of land and water resources. Therefore, understanding the nature and causes of this inter-annual to multi-decadal variability in hydro-climate is important for an integrated assessment of the effects of climate variability on water yield versus those due to climate change. Sauchyn *et al.* (2008) recommend that an additional criterion for evaluating the applicability of GCMs should be their ability to simulate inter-annual to decadal climate variability, particularly for a climate like Alberta's.

The calibrated HSPF model calibrated for the Athabasca River Basin was used on the Firebag River sub-basin to generate a baseline (1961-1990) as well as a 55-year (1954-2007) series of flows using available data at the Fort McMurray Airport climate station. Figure 5.5 shows that the observed and simulated flow statistics for the period of record are comparable. Appendix K provides detailed information on the analysis carried out on the Firebag River sub-basin.

It is assumed that the simulated 55-year flow data series may capture the variability due to past ENSO events and possibly some past PDO events to a greater extent than the standard 30-year (1961-1990) series. Table 5.9 shows the forecasted changes in flow statistics for the 1954-2007 period due to the 2020s and 2050s climate change scenarios.

The effect of future climate scenarios on flow variability was assessed by comparing the standard deviation and coefficient of variation for the two (1961-1990 and 1954-2007) annual flow series under the baseline, 2020s and 2050s climate scenarios. Figure 5.6 shows the simulated annual mean flows for the 1954-2007 period when observed climate data are available and the flow series using the 2020s and 2050s climate change scenarios. It is apparent from Figure 5.6 that the period from 1954 to 1974 was relatively wet compared to the period from 1975 to 2007, with the period from 1954 to 2007 likely reflecting a low frequency wet-dry cycle. The period from 1961 to 1990 (standard climate baseline period) would also encompass portions of the wet and dry cycles. Table 5.10 compares the statistics of the 1961-1990 and 1954-2007 series using the 2020s and 2050s climate change scenarios. The coefficients of variation shown in Table 5.10 suggest that there is no difference (difference not statistically significant) between the baseline 1961-1990 and 1954-2007 series, as well between the same two series under the five climate scenarios for the 2020s and 2050s. One reason for the lack of difference between the two series (30-year and 54-year) is likely because the 54-year is still too short and does not include the extreme wet and dry cycles of the past as suggested by analysis of tree-ring records. It is important to consider the probability and potential for the occurrence of very extreme events, either excessive moisture or drought, that are not reflected in the 30-year1961-1990 baseline for "current climate". However, since the interaction of the various natural climate cycles is not entirely understood, and the complicating effects of a warmer climate add another layer of complexity, this is a relatively new area of research in climate science. Tree ring records, for example, indicate that longer, more frequent and more severe drought periods have occurred in the past on the prairies, but linking climate change feedbacks to these observations to express the probability and severity of these extreme events in the future is very challenging.

The assessment of climate variability in the LARP area will always be constrained by the lack of relatively long (> 100 years) instrumental data records. Analysis of tree-rings can provide some information on past climate and streamflow variability, however, this information cannot be replicated with or incorporated into continuous simulation hydrologic models such as HSPF. One alternative approach is to generate synthetic series of temperature, precipitation and flows using the statistical characteristics of past and present tree-ring records in conjunction with the relationship between present tree-ring records and observed climate and flow data series.

Figure 5.5 Comparison of Observed and Simulated Flow Statistics for the Firebag River Sub-Basin

Simulated and Observed Flow Statistics for Firebag River near the Mouth (07DC001)

Statistic	Recorded (75-86)	Simulated (75-86)	Diff (%)
Mean Annual Flow (m^3/s)	23.3	23.8	2%
Mean Open-Water Flow (m^3/s)	32.2	31.9	-1%
2-Year Peak Flow (m^3/s)	79.7	80.6	1%
10-Year Peak Flow (m^3/s)	171	128	-25%
25-Year Peak Flow (m^3/s)	243	156	-36%
Mean Monthly Flows (m^3/s)			
Jan	9.49	10.6	12%
Feb	8.53	9.36	10%
Mar	8.83	9.00	2%
Apr	26.8	28.8	8%
May	56.3	55.7	-1%
Jun	31.7	29.3	-7%
Jul	28.9	26.6	-8%
Aug	24.9	27.5	11%
Sep	29.5	29.5	0%
Oct	27.5	25.9	-6%
Nov	16.2	19.1	18%
Dec	11.0	14.1	28%

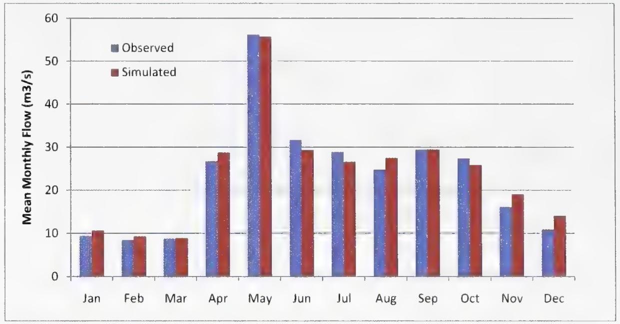

Table 5.9 Effects of 2020s and 2050s Climate Change Scenarios on Baseline (1954 - 2007) Flow Statistics for the Firebag River Sub-Basin

	Baseline Flows (1954-2007)	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
		Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	27.3	-10%	-5%	7%	8%	2%
Mean Open-Water Flow (m^3/s)	37.5	-10%	-6%	8%	8%	1%
2-Year Peak Flow (m^3/s)	91.7	-9%	-10%	10%	5%	0%
10-Year Peak Flow (m^3/s)	177	-9%	-17%	10%	4%	-4%
25-Year Peak Flow (m^3/s)	235	-12%	-23%	10%	5%	-8%
Mean Monthly Flows (m^3/s)						
Jan	12.0	-9%	0%	2%	5%	5%
Feb	10.4	-8%	1%	1%	4%	4%
Mar	9.2	-6%	5%	0%	3%	3%
Apr	32.9	22%	13%	0%	6%	4%
May	62.7	-10%	-20%	7%	1%	-4%
Jun	35	-11%	-5%	11%	10%	0%
Jul	32	-19%	0%	19%	16%	-7%
Aug	36	-25%	-11%	16%	8%	-6%
Sep	35.1	-17%	-8%	4%	12%	10%
Oct	28.6	-7%	0%	0%	12%	14%
Nov	19.4	-8%	2%	4%	10%	9%
Dec	14.6	-9%	0%	4%	8%	6%

	Baseline Flows (1954-2007)	CCSRNIES-A1F1-2050s	CGCM-B23-2050s	HADCM3-A2A-2050s	HADCM3-B2B-2050s	NCARPCM-A1B-2050s
		Change (%)	Change (%)	Change (%)	Change (%)	Change (%)
Mean Annual Flow (m^3/s)	27.3	-6%	-17%	7%	7%	0%
Mean Open-Water Flow (m^3/s)	37.5	-4%	-17%	9%	8%	0%
2-Year Peak Flow (m^3/s)	91.7	2%	-22%	13%	6%	2%
10-Year Peak Flow (m^3/s)	177	10%	-15%	17%	8%	1%
25-Year Peak Flow (m^3/s)	235	11%	-12%	20%	10%	-2%
Mean Monthly Flows (m^3/s)						
Jan	12.0	-12%	-14%	-2%	4%	-1%
Feb	10.4	-13%	-15%	-4%	1%	-2%
Mar	9.2	-13%	-12%	-6%	-1%	-2%
Apr	32.9	9%	5%	4%	13%	17%
May	62.7	9%	-26%	11%	5%	0%
Jun	35	10%	-19%	16%	11%	-2%
Jul	32	-12%	-19%	25%	9%	-13%
Aug	36	-25%	-22%	12%	-3%	-11%
Sep	35.1	-21%	-19%	-3%	8%	2%
Oct	28.6	-9%	-15%	-4%	15%	9%
Nov	19.4	-9%	-12%	0%	10%	6%
Dec	14.6	-10%	-14%	0%	7%	3%

Figure 5.6 Baseline and Future Annual Flow Series for the Firebag River Sub-Basin

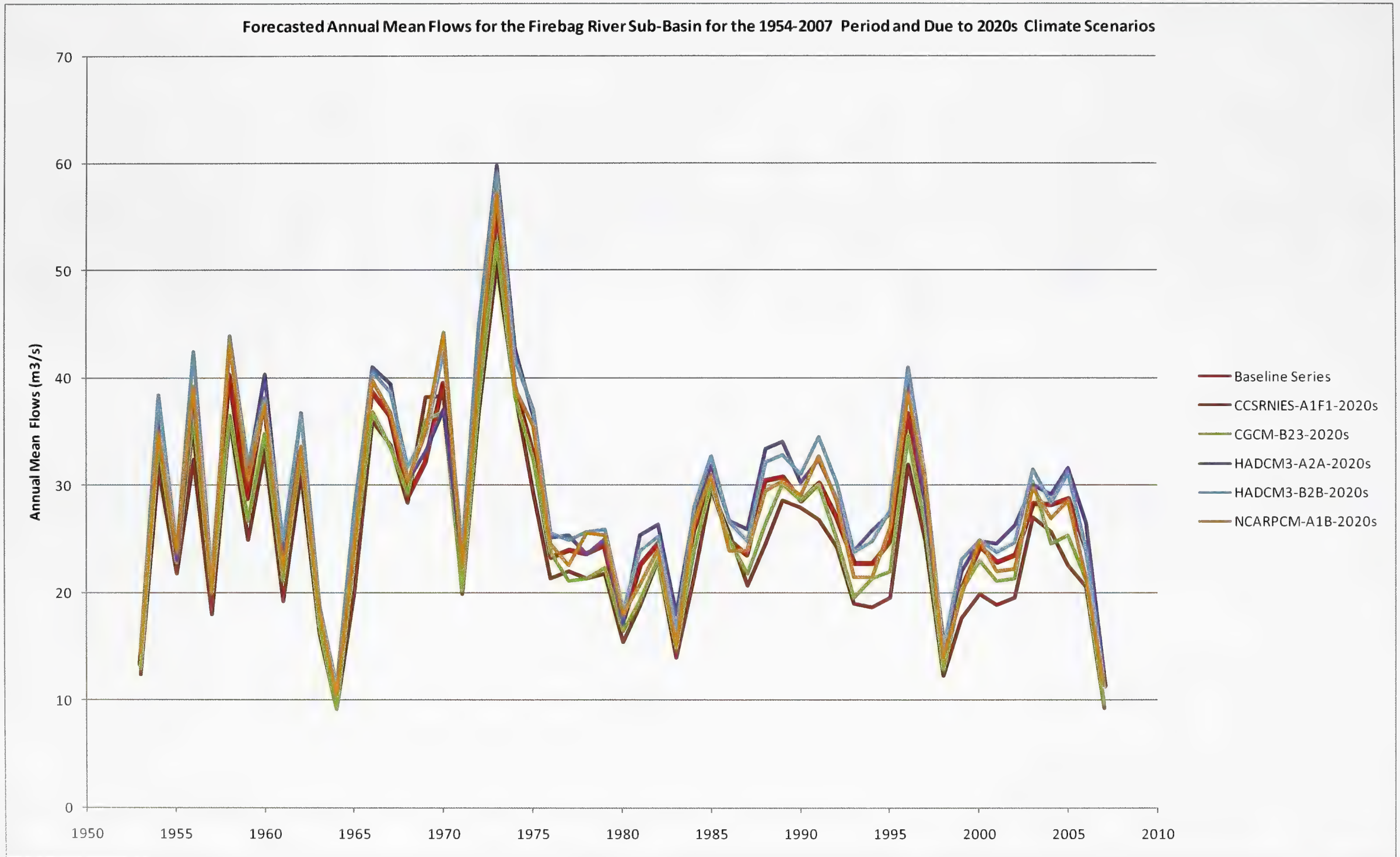

Figure 5.6 Baseline and Future Annual Flow Series for the Firebag River Sub-Basin (continued)

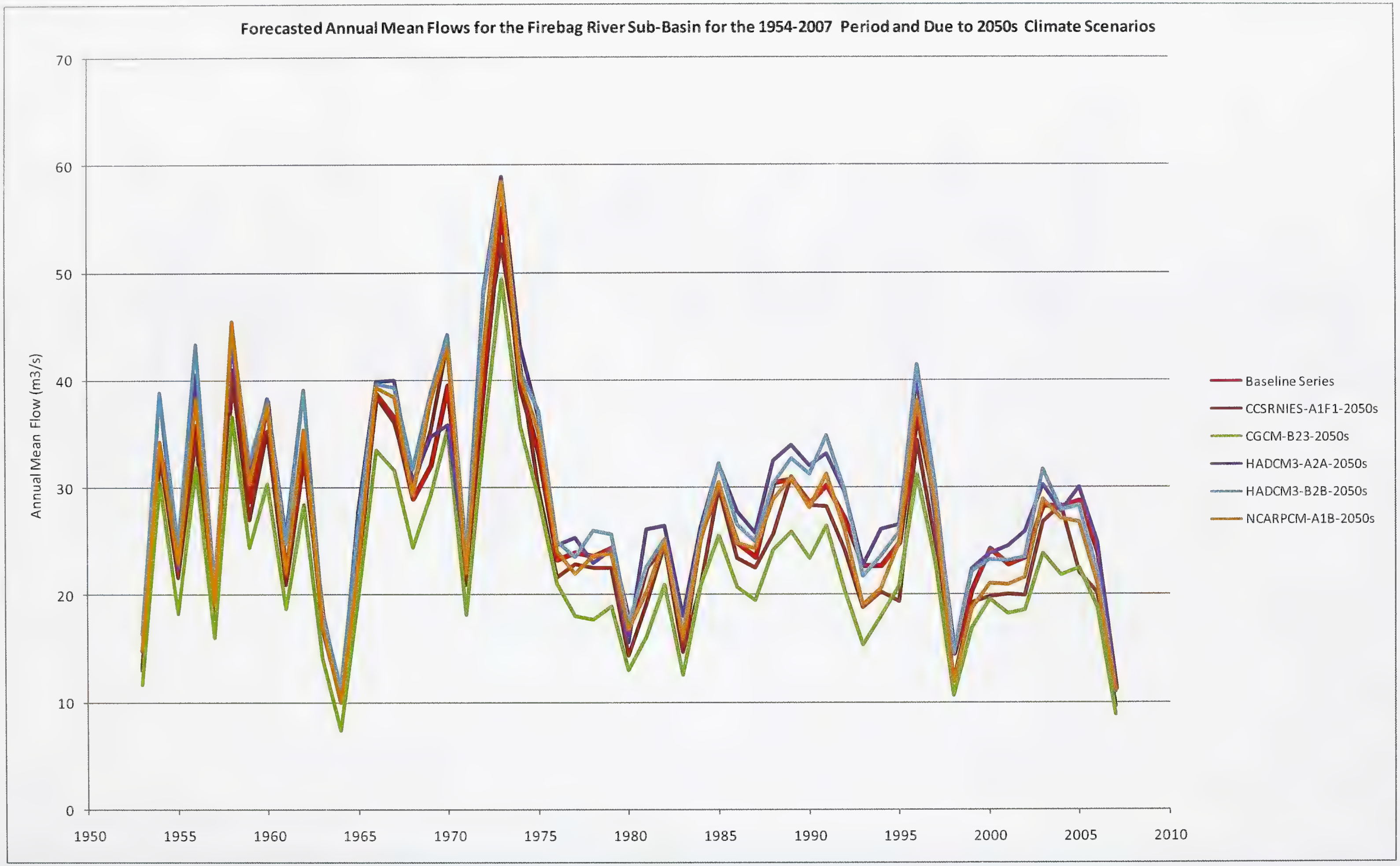

Table 5.10 Comparison of Statistics Derived using the 1961-1990 and the 1954-2007 Flow Series with the 2020s and 2050s Climate Scenarios

2020s Climate Scenarios

Period	Baseline Series	CCSRNIES-A1F1-2020s	CGCM-B23-2020s	HADCM3-A2A-2020s	HADCM3-B2B-2020s	NCARPCM-A1B-2020s
Average 1953-2007	27.4	24.8	26.1	29.3	29.6	27.9
Standard Deviation 1953-2007	8.31	8.20	8.21	8.93	9.17	8.97
Coefficient of Variation 1953-2007	0.30	0.33	0.32	0.30	0.31	0.32
Average 1961-1990	28.1	26.0	26.9	30.0	30.3	28.6
Standard Deviation 1961-1990	9.04	9.00	8.91	9.74	9.74	9.59
Coefficient of Variation 1961-1990	0.32	0.35	0.33	0.32	0.32	0.33

2050s Climate Scenarios

Period	Baseline Series	CCSRNIES-A1F1-2050s	CGCM-B23-2050s	HADCM3-A2A-2050s	HADCM3-B2B-2050s	NCARPCM-A1B-2050s
Average 1953-2007	27.4	25.9	22.8	29.3	29.4	27.5
Standard Deviation 1953-2007	8.31	9.05	7.93	9.27	9.58	9.48
Coefficient of Variation 1953-2007	0.30	0.35	0.35	0.32	0.33	0.34
Average 1961-1990	28.1	27.3	23.6	30.2	30.3	28.7
Standard Deviation 1961-1990	9.04	9.81	8.67	10.03	10.15	10.12
Coefficient of Variation 1961-1990	0.32	0.36	0.37	0.33	0.34	0.35

5.5 Summary

To address the potential effects of climate change on water yield in the Lower Athabasca Regional Plan Area (LARP), which includes the downstream portion of the Athabasca River Basin and the Beaver River Basin, the HSPF model, calibrated and validated for these two basins, has been used to simulate the hydrologic effects of forecasted future climate scenarios. The 1961 to 1990 period was used as the climatological baseline period for the effects assessments.

AENV provided Golder with the Alberta Climate Model data and average monthly changes in temperature and precipitation predicted by five GCMs for two future periods: 2010 to 2039 (referred to as 2020s) and 2040 to 2069 (referred to as 2050s). The differences between the baseline averages and the 2020s averages, and the differences between the baseline averages and the 2050s averages were estimated. The average change in mean annual precipitation varies from -1% to +7% for the 2020s scenarios and from +2% to +13% for the 2050s scenarios. The range of the change in precipitation is much wider on a monthly basis: -10% to +23% for the 2020s scenarios and -15% to +46% for the 2050s scenarios. The average increase in mean annual temperature varies from 0.63°C to 1.52°C for the 2020s scenarios and from 1.77°C to 4.35°C for the 2050s scenarios.

The HSPF model calibrated for the Athabasca River Basin and Beaver River Basin was run with the baseline climate data and the adjusted future climate data. The effects on flows were assessed using the flow statistics at selected locations on the main stem of the Athabasca River and on the Beaver River at the Cold Lake Reserve for the 2020s and 2050s climate scenarios.

General conclusions are as follows:

- All the five climate scenarios for the 2020s tend to result in lower mean annual flows, with the decrease in mean annual flow becoming more severe downstream along the Athabasca River.

- Changes in mean monthly flows for the 2020s scenarios tend to be positive (increase relative to baseline values) during the spring months and significantly negative (decrease) during the summer months. The seasonal differences in flows are consistent with the relative effects of increased precipitation (more spring runoff) and increased temperatures during the summer months (higher summer evapotranspiration).

- The 2050s climate scenarios result in changes in mean annual flow that are generally more severe compared to the 2020s scenarios, which is consistent with the forecasted changes in temperature and precipitation.

- The range of effects of future climate regimes on flows in the Lower Athabasca Regional Plan Area (LARP) is summarized below. Three locations are used for the summary: (1) Athabasca River at Athabasca (07BE001) to represent inflow to the LARP area, (2) Athabasca River below McMurray (07DA001) to represent flows in the oil sands region where the amount of water withdrawal is a key consideration in the planning process, and (3) Beaver River at Cold Lake Reserve sub-basin (06AD006) to represent the southern portion of the LARP area.

  The summary results indicate that water yield from the two basins will generally decrease, with the effects (in percentage terms) more significant during the month of August. The effects on low February flows, although reduced, tend to be less (in percentage terms) compared to changes in August flows. Flood flows tend to be higher under the future climate scenarios.

The results of the assessment of the effects of climate change on flows in the Athabasca River and Beaver River basins tend to be in general agreement with recent studies carried out by independent researchers. Kerkhoven and Gan (2006) predicted that mean annual flows in the ARB would decrease by almost 25% by the last 30 years of the century. Pietroniro and Toth (2006) predict general reduction in flows in the SSRB ranging from -13% to -4%.

The range of effects predicted by the HSPF model for the LARP area is generally consistent with the results of similar studies in Alberta. Depending on the flow statistic, the range of effects can span more than 10%, which reflects the assumptions inherent in the formulation of the climate scenarios as well as uncertainties in the predictions. The range of hydrologic effects predicted by the HSPF model for the LARP area reflects the range of conditions that basin planners should consider. Hence, the predicted effects using HSPF and future climate scenarios provide a rational basis for water management and planning purposes in the LARP area.

The scope of work for this study included an assessment of flow variability relative to effects due to forecasted climate scenarios. The calibrated HSPF model calibrated for the Athabasca River Basin was used on the Firebag River sub-basin to generate a baseline (1961-1990) as well as a 54-year (1954-2007) series of flows using available data at the Fort McMurray Airport climate station. It was assumed that the simulated 55-year flow data series may capture the variability due to past ENSO events and possibly some past PDO events to a greater extent than the standard 30-year (1961-1990) series. The effect of future climate scenarios on flow variability was assessed by comparing the standard deviation and coefficient of variation for the two (1961-1990 and 1954-2007) annual flow series under the baseline, 2020s and 2050s climate scenarios. The calculated coefficients of variation suggest that there is no difference (difference not statistically significant) between the baseline 1961-1990 and 1954-2007 series, as well between the same two series under the five climate scenarios for the 2020s and 2050s. One reason for the lack of difference between the two series (30-year and 54-year) is likely because the 54-year is still too short and does not include the extreme wet and dry cycles of the past as suggested by analysis of tree-ring records.

6.0 CLOSURE

This report presents the outcome of the assessment of hydrologic models for the Lower Athabasca Regional Plan Area and the results of the HSPF model calibration and validation, and simulations with baseline (1961-1990) and climate change (2020s and 2050s) scenarios. Please direct any questions or clarifications regarding the contents of this draft report to Anil Beersing at (403) 260 2292.

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8.0 REFERENCES

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, J., 1986, An introduction to the European hydrological system—Système Hydrologique Européen, 'SHE', 1: History and philosophy of a physically-based, distributed modelling system, *J. of Hydrology*, 87, 45–59.

Alberta Environment (AENV). 2006. Cold Lake-Beaver River – Surface Water Quantity and Aquatic Resources – State of the Basin Report. February 2006.

Alberta Environment. 2005. Alberta Climate Model (ACM) to provide climate estimates (1961-1990) for any location in Alberta from its geographic coordinates. Publ. No. T/749. Alberta Environment. 35 pp.

Barrow E. and G. Yu. 2005. Climate Scenarios for Alberta. A Report Prepared for the Prairie Adaptation Research Collaborative (PARC) in co-operation with Alberta Environment. May 2006.

Beven, K. J., Lamb, R., Quinn, P., Romanowicz, R., and Freer, J., 1995, TOPMODEL, In *Computer Models of Watershed Hydrology*, edited by V. P. Singh (Fort Collins, Colorado: Water Resources Publications), pp. 627–668.

Biftu, G. F., and T.Y. Gan, Semi-distributed, Hydrologic Modeling of Dry Catchment with Remotely Sensed and Digital Terrain Elevation Data, *Int. J. Remote Sensing*, 25(20), 4351-4379, Oct., 2004.

Biftu, G. F., and T.Y. Gan, Semi-distributed, Physically Based, Hydrologic Modeling of the Paddle River Basin, Alberta using Remotely Sensed data, *J. of Hydrology,* 244, p. 137-156, 2001.

Burnash, R. J., Ferral, R. L., and Mcquire, R. A., 1973, A generalized stream flow simulation system. Conceptual modelling for digital computers (Sacramento, California: US National Weather Service).

Crawford, N. H., and Linsley, R. K., 1966, *Digital simulation in hydrology: Stanford Watershed Model IV*, Dept. of Civil Engineering, Stanford University, Tech. Rept. No. 39.

Fortin, J. P., Villeneuve, J. P., Guibot, A., and Seguin, B., 1986, Development of a modular hydrological forecasting model based on remotely sensed data, for interactive utilization on a microcomputer. *Hydrologic Applications of Space Technology*, 307–319.

Golder Associates Ltd. (Golder). 2006. Hydrologic Regions of Alberta. Prepared for Alberta Environment. March 2006.

Hydrologic Engineering Center, 1998, HEC-HMS, *Hydrologic modeling system and User's Manual*, U. S. Army Corps of Engineers, Davis, California.

IPCC (Intergovernmental Panel on Climate Change). 2000. Special Report on Emissions Scenarios. N. Nakicenovic and R. Swart (ed.). Cambridge University Press. Cambridge, United Kingdom. 612 pp.

Kerkhoven, E., and Gan, T. Y., 2005, Modeling Hydrologic Responses of Athabasca River Basin to Climate Change by Modified ISBA Land Surface Scheme, *Proceedings of Symposium S6, 7th IAHS Scientific Assembly*, IAHS Publ., 296, 89-101.

Kerkhoven E, Gan T.Y., 2006, A modified ISBA surface scheme for modeling the hydrology of Athabasca River Basin with GCM-scale data, *Advanced Water Resources*, 29: 808-826.

Kite, G. W., 1995, Scaling of input data for macroscale hydrologic modelling, *Water Resources Research*, 31, 2769–2781.

Kouwen, N., 1988, WATFLOOD, a micro-computer based flood forecasting system based on real-time weather radar, *Canadian Water Resources Journal*, 13, 62–77.

Liang X, Lettenmaier DP, and Wood EF., 1996, One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model, *J Geophys Res*, 101(D16): 21,403-22.

Liang, X., Xie, Z., 2001, A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models, *Advances in Water Resources*, 24(9-10): 1173-1193.

Noilhan J and Planton S, A simple parameterization of land surface processes for meteorological models, *Mon. Wea. Rev.*,1989;117:536–49.

Pietroniro A., B. Toth and J. Toyra. 2006. Water Availability in the South Saskatchewan River Basin under Climate Change – Physical Modelling Component. Presented to the Climate Change and Water in the Prairies Conference, Saskatoon, SK. June 2006.

Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N. R.,Quinton, W. L.,Granger, R., and Carey, S. K., 2007, The Cold Regions Hydrological Model, a Platform for Basing Process Representation and Model Structure on Physical Evidence, *Hydrologic Processes*.

Regional Aquatics Monitoring Program (RAMP). http://www.ramp-alberta.org/river.aspx. Accessed 20 June 2009.

Sauchyn, D. and Kulshreshtha, S. 2008. Prairies; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, *edited by* D.H. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 275-328.

Sauchyn D., E. Barrow and S. Lapp. 2008. Explorations of Climate Variability in Alberta: Past, Present and Future. Prepared for Alberta Environment as part of the Alberta Biophysical Vulnerability Assessment Project. March 2008.

Science Outreach. http://scienceoutreach.ab.ca/athabasca_region.htm. Accessed 20 June 2009.

University of Alberta. 2005. Atlas of Alberta Lakes.

APPENDIX A

Detailed Evaluations of Hydrologic Models

Table A.1 Scores and Ranking of Hydrologic Models for the Hydro-Climate Modelling of the Lower Athabasca Region

Criterion	Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	WATFLOOD	MISBA	MIKE-SHE	HSPF	HEC-HMS	HYDROTEL	SSARR	DPHM-RS	VIC	CRHM	WATFLOOD	MISBA	MIKE-SHE	HSPF	HEC-HMS	HYDROTEL	SSARR	DPHM-RS	VIC	CRHM
																TOTAL MODEL SCORE									
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value			How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated										480	420	519	492	390	450	421	503	502	498
Ability to Incorporate Key Features of Watershed being Modelled																									
	Physical Characteristics (Area, Elevation, Slope, etc)		5			5	4	5	4	4	5	3	5	5	4	25	20	25	20	20	25	15	25	25	20
	Stream Characteristics		3			4	0	5	3	3	4	3	4	4	3	12	0	15	9	9	12	9	12	12	9
	Surficial Geology/Soil Characteristics		3			4	4	4	3	3	4	0	4	4	4	12	12	12	9	9	12	0	12	12	12
	Land Cover/Vegetation Characteristics		2			4	5	5	3	2	5	2	5	4	4	8	10	10	6	4	10	4	10	8	8
	Non-contributing Runoff Areas		4			2	2	2	2	0	0	0	2	2	4	8	8	8	8	0	0	0	8	8	16
Ability to Simulate Key Hydrologic Processes in Watershed being Modelled																									
	Rainfall-Runoff		5			3	3	5	4	4	4	3	4	4	3	15	15	25	20	20	20	15	20	20	15
	Snowmelt-Runoff		5			3	3	3	4	3	3	5	4	4	3	15	15	15	20	15	15	25	20	20	15
	Interflow		5			3	0	3	4	3	4	3	2	0	3	15	0	15	20	15	20	15	10	0	15
	Infiltration		4			4	3	5	4	3	3	3	4	4	3	16	12	20	16	12	12	12	16	16	12
	Interception		3			3	5	5	4	3	0	3	5	5	5	9	15	15	12	9	0	9	15	15	15
	Baseflow		3			4	4	5	4	3	3	3	4	4	3	12	12	15	12	9	9	9	12	12	9
	Lake Evaporation		3			3	4	3	3	0	3	0	3	3	3	9	12	9	9	0	9	0	9	9	9
	Evapotranspiration		3			3	5	3	3	3	4	3	5	4	4	9	15	9	9	9	12	9	15	12	12
	Snow sublimation		3			3	4	3	3	0	0	0	4	4	4	9	12	9	9	0	0	0	12	12	12
	Snow transport/re-distribution		3			0	0	0	0	0	0	3	0	4	4	0	0	0	0	0	0	9	0	12	12
Ability to Simulate Processes on Event to Multi-year Basis																									
	Event-simulation only		0			5	5	5	5	4	4	3	0		3	0	0	0	0	0	0	0	0	0	0
	Continuous Simulation		5			5	5	5	5	3	5	4	5	5	4	25	25	25	25	15	25	20	25	25	20
Ability to Simulate Key Hydraulic Features																									
	Channel Routing		5			3	0	5	3	3	4	4	4	4	3	15	0	25	15	15	20	20	20	20	15
	Storage in/Outflow from Lakes/Wetlands		3			3	0	4	4	4	4	5	4	4	4	9	0	12	12	12	12	15	12	12	12
	Floodplain Routing and Storage		2			3	0	5	0	0	0	3	0	0	0	6	0	10	0	0	0	6	0	0	0
	Flow under Ice Cover		0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ice jams and/or break-up		0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ability to Provide Outputs at Varying Spatial Scale of Interest within Watershed being Modelled																									
	Watershed		5			5	5	5	5	5	5	5	5	5	5	25	25	25	25	25	25	25	25	25	25
	Sub-basin		5			4	3	4	4	5	4	4	4	4	4	20	15	20	20	25	20	20	20	20	20
	Local Drainage/Landscape Feature		2			3	2	4	3	0	2	0	3	3	4	6	4	8	6	0	4	0	6	6	8
Ability to Provide Outputs at Time Scale of Interest																									
	Annual		5			5	3	5	5	2	2	4	2	2	2	25	15	25	25	10	10	20	10	10	10
	Daily		5			5	4	5	5	5	4	4	4	4	4	25	20	25	25	25	20	20	20	20	20
	Hourly		3			5	2	5	5	5	5	4	5	5	4	15	6	15	15	15	15	12	15	15	12
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements		Availability of Data ? 5: Available at required resolution 4: Available but at lower though useful resolution 3: Can be generated with some effort and time 2: Would require considerable effort and time to acquire 1: May not be available 0: Not available				Data Format/Resolution Required by Model: Yes: 1 No: 0																			
Climate																									
	Ability of Model to Use Format of Downscaled Climate Data					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	2	2	5	2	5	5	2
	With no or minimal pre-processing			5		1	1	1			1		1	1		5	5	5	0	0	5	0	5	5	0
	With considerable pre-processing			2					1	1	0	1			1	0	0	0	2	2	0	2	0	0	2
	Temperature: Min Max Avg					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	5	5	5	5
		Point/Gauge		5		1	0	1	1	1	1	1	1	1	1	5	0	5	5	5	5	5	5	5	5
		Grid cell		5		1	1	1	0	1	1	0	0	1	0	5	5	5	0	5	5	0	0	5	0
		Sub-basin		3		0	0	1	1	1	0	1	1	0	0	0	0	3	3	3	0	3	3	0	0
	Rain					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	5	5	5	5
		Point/Gauge		5		1	0	1	1	1	1	1	1	1	1	5	0	5	5	5	5	5	5	5	5
		Grid cell		5		1	1	1	0	1	1	0	0	1		5	5	5	0	5	5	0	0	5	0
		Sub-basin		3			0	1	1	1	0	1	1	0		0	0	3	3	3	0	3	3	0	0
	Snow					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	5	5	5	5
		Basin average snow depth		4				1	1		0		0			0	0	4	4	0	0	0	0	0	0
		Grid cell		5		1		1			1		0			5	0	5	0	0	5	0	0	0	0
		Point/Gauge Water Equivalent		5		1	1	1	1	1	1	1	1	1	1	5	5	5	5	5	5	5	5	5	5
	Solar Radiation					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										0	5	5	3	5	5	5	3	5	5
		Hourly		3		0	1	1	1	1	1	1	1	1	1	0	3	3	3	3	3	3	3	3	3
		Daily		5		0	1	1	0	1	1	1	0	1	1	0	5	5	0	5	5	5	0	5	5
	Wind					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										3	5	5	3	0	5	5	5	5	5
		Hourly		3		0	1	1	1	0	1	1	1	1	1	0	3	3	3	0	3	3	3	3	3
		Daily		5		0	1	1	0	0	1	1	1	1	1	0	5	5	0	0	5	5	5	5	5
	Relative Humidity	Daily		3		1	1	1	1	0	1	1	1	1	1	3	3	3	3	0	3	3	3	3	3
	Cloud ness	Daily		2		0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0
Discretization of Watershed						Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	3	5	5	5	5	5	5	3	5
	Sub-basins			5		0	0	1	1	1	1	1	1	0	1	0	0	5	5	5	5	5	5	0	5
	Elevation contours			5		1	0	1	0			1	1	0	0	5	0	5	0	0	0	5	5	0	0
	DEM Grid Cells			3		1	1	1	0		1	0	1	1	0	3	3	3	0	0	3	0	3	3	0
Representation of Streams						Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										2	0	3	3	3	2	3	3	2	3
	GIS-based Hydrography			2		1	0	1	0		1	0	1	1	0	2	0	2	0	0	2	0	2	2	0
	Conceptual Storage Elements/Schematized Network			3		0	0	1	1	1	0	1	1	0	1	0	0	3	3	3	0	3	3	0	3
Geology																									
	Surficial Geology Soil Characteristics			3		1	1	1	1	1	1	0	1	1	1	3	3	3	3	3	3	0	3	3	3
Vegetation Coverage																									
	Muskeg			3		0	0	1	1		0	0	0	0	0	0	0	3	3	0	0	0	0	0	0
	Forest			5		1	1	1	1	1	1	1	1	1	1	5	5	5	5	5	5	5	5	5	5
	Grass			4		1	1	1	1	1	1	0	1	1	1	4	4	4	4	4	4	0	4	4	4
	Cleared Areas			5		1	1	1	1	1	1	0	1	1	1	5	5	5	5	5	5	0	5	5	5

Criteria	Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL	WATFLOOD	MISBA	MIKE-SHE	HSPF	HEC-HMS	HYDROTEL	SSARR	DPHM-RS	VIC	CRHM	WATFLOOD	MISBA	MIKE-SHE	HSPF	HEC-HMS	HYDROTEL	SSARR	DPHM-RS	VIC	CRHM
															TOTAL MODEL SCORE									
Criteria and Sub-Criteria for Degree of Sophistication of Processes Simulated in Model - REGION DEPENDENT					How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated																			
Rainfall-Runoff					The maximum score for each criterion will be used in the total model score										16	12	15	12	15	20	15	12	12	16
	Unit Hydrograph	3			0	0	0	0	5	0	0	0	4	0	0	0	0	0	15	0	0	0	12	0
	Conceptual storages	3			0	0	4	4	3	0	5	0	0	0	0	0	12	12	9	0	15	0	0	0
	Hydrologic Response Units	4			4	0	0	0		5	0	3	0	4	16	0	0	0	0	20	0	12	0	16
	Water Balance at Grid Cell Level	3			0	4	5	4		4	3	4	3	3	0	12	15	12	0	12	9	12	9	9
Snowmelt-Runoff					The maximum score for each criterion will be used in the total model score										4	25	4	15	3	4	20	20	20	20
	Degree day	1			4	0	4	4	3	4	3	3	0	3	4	0	4	4	3	4	3	3	0	3
	Energy Equations	5				5	0	3			4	4	4	4	0	25	0	15	0	0	20	20	20	20
Evaporation/Evapotranspiration					The maximum score for each criterion will be used in the total model score										20	25	0	9	0	20	9	20	20	25
	Energy Equations	5			4	5	0			4	0	4	4	5	20	25	0	0	0	20	0	20	20	25
	External Approach such as Morton's Approach	3			0	0	0	3	0	0	3	0	0	3	0	0	0	9	0	0	9	0	0	9
	Pan Evaporation	0			3	0	3		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Routing in Stream Reaches					The maximum score for each criterion will be used in the total model score										12	0	15	9	9	9	12	12	12	9
	Hydrograph Translation	1			0	0	4	0	3		3	0	0	0	0	0	4	0	3	0	3	0	0	0
	Muskingum or other routing approach	3			4	0	5	3	3	3	4	4	4	3	12	0	15	9	9	9	12	12	12	9
Infiltration					The maximum score for each criterion will be used in the total model score										9	12	9	9	9	3	0	12	9	9
	Physics-based Spatial and Temporal Distribution	1			4	4	4	3		3	0	4	4	4	4	4	4	3	0	3	0	4	4	4
	Average based on soil type	3			3	4	3	3	3		0	4	3	3	9	12	9	9	9	0	0	12	9	9
Criteria Defining Ease of Using Models																								
Model Availability					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										4	3	0	5	5	4	5	0	0	0
	Commercial-Wide Use	5					1								0	0	5	0	0	0	0	0	0	0
	Commercial-Limited Use	4			1										4	0	0	0	0	0	0	0	0	0
	Public Domain-Wide Use	5						1	1		1				0	0	0	5	5	0	5	0	0	0
	Public Domain-Limited Use	4								1					0	0	0	0	0	4	0	0	0	0
	Research-Real World Applications	3				1									0	3	0	0	0	0	0	0	0	0
	Research-Limited Application	0										1	1	1	0	0	0	0	0	0	0	0	0	0
	Research-Under Development	0			1										0	0	0	0	0	0	0	0	0	0
Training/Support					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										0	0	3	3	3	3	3	0	0	3
	Training provided by developers	3			0	0	1	1				0	0		0	0	3	3	0	0	0	0	0	0
	Training provided by consultants	3			0	0	1	1		1	1	0	0		0	0	3	3	0	3	3	0	0	0
	Frequent training workshops	3			0	0	1	1	1			0	0	1	0	0	3	3	3	0	0	0	0	3
Operating System					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										2	2	5	5	5	0	5	2	5	5
	Win 95	0				0	1	1	1	1	1			1	0	0	0	0	0	0	0	0	0	0
	Win 98	0				0	1	1	1	1	1			1	0	0	0	0	0	0	0	0	0	0
	Win 2000	5				0	1	1	1		1		1	1	0	0	5	5	5	0	5	0	5	5
	UNIX	0			1	1		1					1	1	0	0	0	0	0	0	0	0	0	0
	DOS	2			1	1		1			1	1		0	2	2	0	2	0	0	2	2	0	0
	Mac	0				0		0						1	0	0	0	0	0	0	0	0	0	0
Description of Model's Modules					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	5	5	5	5
	Description/Theory of Hydrologic Processes	5			1	1	1	1	1	1		1	1	1	5	5	5	5	5	5	0	5	5	5
	Incorporation of User Comments	3			1	1	1	1		1		1	1	1	3	3	3	3	0	3	0	3	3	3
	Extensive Documentation on Modules	5			1	0.5	1	1	1	1	1	0	1	1	5	2.5	5	5	5	5	5	0	5	5
Modification of Model by User					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										0	5	0	5	0	5	5	5	5	5
	Modifiable by user	5			0	1	0	1	0	1	1	1	1	1	0	5	0	5	0	5	5	5	5	5
	Proprietary Code	0			1	0	1	0	1	0		0	0	0	0	0	0	0	0	0	0	0	0	0
Criteria Defining Calibration and Validation																								
Calibration and Validation					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	5	5	5	5
	Based on events only	2			1	0	0	1	1	1		0	0		2	0	0	2	2	2	0	0	0	0
	Continuous-simulation	5			1	1	1	1	1	1	1	1	1	1	5	5	5	5	5	5	5	5	5	5
					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										3	0	0	4	3	3	4	0	3	3
	Graphics of Observed vs Simulated Outputs	3			0	0	0	1	1	1		0	1	1	0	0	0	3	3	3	0	0	3	3
	Statistics of Observed vs Simulated Outputs	4			0	0	0	1	0		1	0	0		0	0	0	4	0	0	4	0	0	0
	Automatic optimization of calibration parameters	3			1	0	0	0	0			0	1		3	0	0	0	0	0	0	0	3	0
	Expert System	2			0	0	0	1	0			0			0	0	0	2	0	0	0	0	0	0
Criteria Defining Data Management Objectives																								
Compatibility of Data Management in Model with User's System					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										5	5	5	5	5	5	1	5	5	5
	Input via Excel/Access/Other Database	5			1	1	1	1	1	1		1	1	1	5	5	5	5	5	5	0	5	5	5
	Manual Input	1				0	1		1		1				0	0	1	0	1	0	1	0	0	0
	Import GIS/Remote Sensing Files	3			1	1	1	0	1	1		1	1	1	3	3	3	0	3	3	0	3	3	3
					Yes = 1, No = 0 : The maximum score for each criterion will be used in the total model score										3	3	3	3	3	3	3	3	3	3
	Output exportable to Excel	3			1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	Output exportable to GIS	3				1	1	0		1		1		1	0	3	3	0	0	3	0	3	0	3
	Output exportable to common database	3				0	1	1							0	0	3	3	0	0	0	0	0	0

Table A.2 Assessment of WATFLOOD for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	No.	Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL: WATFLOOD		SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4. Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value		How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated		
Ability to Incorporate Key Features of Watershed being Modelled							
	1	Physical Characteristics such as Area, Elevation, Slope			Drainage area of grid (%) and impervious area of the grid (%) are required Contour interval and contour density in each grid, elevation of the main channel in the grid at its midpoint between the element boundaries, and drainage direction and channel density in each grid are required for flow determination		
	2	Soil/Surficial Geology			Different soil classification group as the percentage in each grid are considered by the model Initial soil moisture of the grid is required.		
	3	Vegetation Type/Density			Bareground, forests, and crops are considered as some of the land uses		
	4	Aspect			UTM coordinate of the grid is required		
	5	Anthropogenic Changes in Land Cover			Different land cover/use classes as percentages in each grid are considered by the model		
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)			No		
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled							
	7	Direct Runoff from Rain			Uses Manning's equation for direct surface runoff		
	8	Direct Runoff from Snowmelt			Snowmelt runoff is based on either temperature index model or radiation-temperature index model		
	9	Interflow			Interflow is represented by a simple storage-discharge relation to the Upper Zone Storage, the specific retention of the soil in the upper zone and land surface slope by a parameter to be optimized It is calculated simultaneously with groundwater recharge		
	10	Infiltration/Groundwater			Infiltration uses Philip Formula Groundwater recharge uses simple function as for interflow to the Upper Zone Storage and the specific retention of the soil in the upper zone It is calculated simultaneously with the interflow		
	11	Interception			Interception uses Linsley model This method calculates the total possible interception as the sum of the maximum canopy storage and the amount of interception evapotranspiration during the storm event)		
	12	Baseflow			Baseflow is the groundwater outflow from the lower zone storage determined by a ground water depletion function that has two parameters that need to be optimized		
	13	Winter flows			No		
	14	Lake Evaporation			Lake evaporation is obtained from actual evapotranspiration through the use of a reduction factor a calibration parameter		
	15	Evapotranspiration			Any one of three methods for estimating evapotranspiration can be used: the Priestley-Taylor equation when radiation data are available, the Hargreaves equation when only temperature data are available, when neither data are available, the original method of estimating evapotranspiration from published values can be used.		
	16	Snow sublimation			Based on snow sublimation factor		
	17	Snow transport/re-distribution			No		
Ability to Simulate Processes on Event to Multi-year Basis							
	18	Event-simulation only			No		
	19	Continuous Simulation			Yes		
Ability to Simulate Key Hydraulic Features							
	20	Main Channel Routing			Yes Using storage routing technique		
	21	Routing through a Network of Channels			Yes Flow in reaches can be routed by storage routing		
	22	Storage in Lakes/Wetlands			Yes		
	23	Floodplain Routing and Storage			Yes		
	24	Flow under Ice Cover			No		
	25	Ice jams and/or break-up			No		
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled							
	26	Watershed			Yes		
	27	Sub-basin			Yes		
	28	Local Drainage/Landscape Feature			Yes		
	29	Hillslope catchment			No		
	30	Lakes/Wetlands			Yes		
	31	Perched Basins			No		
	32	Beaver Dams			No		
Ability to Provide Outputs at Time Scale of Interest							
	33	Annual			Yes		
	34	Monthly			Yes		
	35	Daily			Yes		
	36	Hourly			Yes		
Ability of Model to Use Format of Downscaled Climate Data							
	37	With no or minimal pre-processing			No The program has to be customized for each radar source because of the different formats in use		
	38	With considerable pre-processing			Yes		
[illegible] Model's Data/Scale/Resolution Requirements							
Climate							
	39	**Temperature: Min Max Avg**			**Min & Max**		
					Point	Yes	
					Grid cell	Yes	
					Sub-basin	No	
	40	**Rain**					
					Point	Yes, when radar data is not available	
					Grid cell	Yes, from radar	
					Sub-basin	No	
					Isohyets	No	
					Thiessen Polygons	No	
	41	**Snow**				**Hourly total**	
					Snow pillow	No	
					Average snow depth	No	
					Snow depth by land/vegetation class	Yes	
					Snow density	No	
					Snow water equivalent	Yes	
	42	**Solar Radiation**					
					Hourly	No	
					Daily	No	
	43	**Wind**					
					Hourly	No	
					Daily	No	
	44	Relative Humidity			Daily	Yes, monthly values	
	45	Cloudiness			Daily	No	
	46	Evaporation			Daily	No, Can be calculated from other data	
	47	Evapotranspiration			Daily	No, Can be calculated from other data	
[illegible]							
	48	Grid cells			Yes		
	49	Sub-basins			No		
	50	Elevation contours			Yes		
	51	DEM			Yes		
[illegible]							
	52	[illegible] hydrography			Yes		
	53	Conceptual Schematized Network			No		
	54	Storage Elements			No		
[illegible]							
	55	[illegible]			No		
	56	[illegible]			Yes		
[illegible]							
	57	[illegible]			No		

Criterion		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	WATFLOOD	
[illegible]teria and Sub-Criteria Relevant to [illegible]jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes					
	59	Grass	Yes					
	60	Cleared Areas	Yes					
[illegible] Sophistication of Processes [illegible]nulated in Model - REGION [illegible]EPENDENT								
[illegible]								
	61	Unit Hydrograph	No					
	62	Conceptual storages	Yes					
	63	Hydrologic Response Units	Yes					
	64	Water Balance	Yes					
[illegible]								
	65	Degree day	Yes					
	66	Energy Equations	Yes					
[illegible]								
	67	Energy Equations	Yes					
	68	Morton's Approach	No					
	69	Pan Evaporation	Yes					
[illegible]								
	70	Hydrograph Translation	No					
	71	Muskingum	Yes - Storage Routing					
[illegible]								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	Yes					
[illegible]								
	74	Based on temperature	No					
	75	Steady rate	Yes					
[illegible]								
Model Availability								
	76	Commercial-Wide Use						
	77	Commercial-Limited Use	Yes					
	78	Public Domain-Wide Use						
	79	Public Domain-Limited Use						
	80	Research-Real World Applications						
	81	Research-Limited Application						
	82	Research-Under Development	Yes					
[illegible]								
	83	Training provided by developers						
	84	Training provided by consultants						
	85	Frequent training workshops						
	86	Help Files and Example Applications	yes					
[illegible]								
	87	Win 95						
	88	Win 98						
	89	Win 2000						
	90	UNIX	Yes					
	91	DOS	Yes					
	92	Mac						
	93	Single computer station						
	94	Multiple users on network						
[illegible]								
	95	Theory of Hydrologic Processes						
	96	Assumptions and Approximations						
	97	Incorporation of User Comments						
	98	Extensive Documentation						
[illegible]								
	99	Modifiable by user	No					
	100	Proprietary Code	Yes					
[illegible]idation								
Calibration and Validation								
	101	Event-based only	No					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	Yes					
	104	Statistics of Observed vs Simulated Outputs	No					
	105	Automatic optimization of calibration parameters	Yes					
	106	Expert System	No					
[illegible]jectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel						
	108	Internal Database - Manual Input	No					
	109	Input via Access or other database						
	110	Import GIS Files						
	111	Import Remotely Sensed Data	Yes					
	112	Output exportable to Excel	Yes					
	113	Output exportable to GIS						
	114	Output exportable to common database						
[illegible]rry out uncertainty analyses								
[illegible] Analysis								
	115	Monte Carlo Approach - User defined input probability distributions						
	116	Use synthesized input data series						

Table A.3 Assessment of MISBA for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	No.	Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL: MISBA	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value		How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
Ability to Incorporate Key Features of Watershed being Modelled						
	1	Physical Characteristics such as Area, Elevation, Slope	Percent of area for three surfaces natural (vegetation and bare soil), urban areas and water bodies is used to evaluate hydrologic processes at point scale and then aggregated according to the proportions of areas of these surfaces present within the sub-grid Elevation, slope and aspect used to derive topographic-soil index that is required sub-surface simulation			
	2	Soil/Surficial Geology	Spatial distribution of soil types, soil hydraulic properties are required to evaluate soil moisture water balance using a generalized form of the force-restore method (similar to VIC model)			
	3	Vegetation Type/Density	Hydrologic processes are evaluated for different land covers at point scale and then aggregated according to the proportions of the land cover present within the grid scale.			
	4	Aspect	Elevation, slope and aspect used to derive flow directions, stream order, and topographic-soil index that is required for groundwater simulation			
	5	Anthropogenic Changes in Land Cover	Different land uses can be considered by the model			
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)	No			
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled						
	7	Direct Runoff from Rain	Sub-grid runoff and sub-grid drainage			
	8	Direct Runoff from Snowmelt	Snowmelt runoff based on energy method			
	9	Interflow	No explicit method to simulate interflow Interflow is aggregated with surface runoff			
	10	Infiltration/Groundwater	Soil moisture water balance similar to VIC model **Recent modification for sub-surface runoff (groundwater) using topographic soil index**			
	11	Interception	Interception storage is removed by evaporation, canopy sloarge varies with LAI			
	12	Baseflow	Baseflow determined by topographic-soil index approach developed by Sivapalan et al (1987) **This is recent addition to the model**			
	13	Winter flows	No			
	14	Lake Evaporation	Based on lake evaporation determined by Energy Balance.			
	15	Evapotranspiration	Evapotranspiration is simulated using the 3-layer model			
	16	Snow sublimation	It is based on energy available (latent heat and sensible heat exchange) for each land use			
	17	Snow transport/re-distribution	No			
Ability to Simulate Processes on Event to Multi-year Basis						
	18	Event-simulation only	No			
	19	Continuous Simulation	Yes			
Ability to Simulate Key Hydraulic Features						
	20	Main Channel Routing	No			
	21	Routing through a Network of Channels	No			
	22	Storage in Lakes/Wetlands	No			
	23	Floodplain Routing and Storage	No			
	24	Flow under Ice Cover	No			
	25	Ice jams and/or break-up	No			
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled						
	26	Watershed	Yes			
	27	Sub-basin	Yes			
	28	Local Drainage/Landscape Feature	Yes			
	29	Hillslope catchment	Yes			
	30	Lakes/Wetlands	Yes			
	31	Perched Basins	No			
	32	Beaver Dams	No			
Ability to Provide Outputs at Time Scale of Interest						
	33	Annual	Yes			
	34	Monthly	Yes			
	35	Daily	Yes			
	36	Hourly	Yes			
Ability of Model to Use Format of Downscaled Climate Data						
	37	With no or minimal pre-processing	Yes			
	38	With considerable pre-processing	No			
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements						
Climate						
	39	**Temperature: Min Max Avg**				
			Point	No		
			Grid cell	Hourly/daily average		
			Sub-basin	No		
	40	**Rain**				
			Point	No		
			Grid cell	Hourly/daily total		
			Sub-basin	No		
			Isohyets	No		
			Thiessen Polygons	No		
	41	**Snow**		**Hourly/daily total**		
			Snow pillow	No		
			Average snow depth	No		
			Snow depth by land/vegetation class	No		
			Snow density	Yes		
			Snow water equivalent	Yes		
	42	**Solar Radiation**	**yes**			
			Hourly	Yes		
			Daily	Yes		
	43	**Wind**	**yes**			
			Hourly	Yes		
			Daily	Yes		
	44	Relative Humidity	Daily	Yes, also specific humidity		
	45	Cloudiness	Daily	No		
	46	Evaporation	Daily	No Calculated from other data internally		
	47	Evapotranspiration	Daily	No Calculated from other data internally		
[illegible]						
	48	Grid cells	Yes			
	49	Sub-basins	No			
	50	Elevation contours	No			
	51	DEM	Yes			
[illegible]						
	52	Digitized Hydrography	No			
	53	Conceptual Schematized Network	No			
	54	Storage Elements	No			
[illegible]						
	55	Surficial	No			
	56	Soil	Yes			
[illegible]						
	57	Mapping	No			

[illegible]		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	MISBA	
[illegible]teria and Sub-Criteria Relevant to [illegible]jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes					
	59	Grass	Yes					
	60	Cleared Areas	Yes					
[illegible] Sophistication of Processes [illegible]mulated in Model - REGION [illegible]EPENDENT								
[illegible]								
	61	Unit Hydrograph	No					
	62	Conceptual storages	No					
	63	Hydrologic Response Units	No					
	64	Water Balance	Yes					
[illegible]								
	65	Degree day	No					
	66	Energy Equations	Yes					
[illegible]								
	67	Energy Equations	Yes					
	68	Morton's Approach	No					
	69	Pan Evaporation	No					
[illegible]								
	70	Hydrograph Translation	No					
	71	Muskingum	No					
[illegible]								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	Yes					
[illegible]								
	74	Based on temperature	No					
	75	Steady rate	No					
[illegible]								
Model Availability								
	76	Commercial-Wide Use	No					
	77	Commercial-Limited Use	No					
	78	Public Domain-Wide Use	No					
	79	Public Domain-Limited Use	No					
	80	Research-Real World Applications	Yes					
	81	Research-Limited Application	Yes					
	82	Research-Under Development	Yes					
[illegible]								
	83	Training provided by developers	No					
	84	Training provided by consultants	No					
	85	Frequent training workshops	No					
	86	Help Files and Example Applications	No					
[illegible]								
	87	Win 95						
	88	Win 98						
	89	Win 2000						
	90	UNIX	Yes					
	91	DOS	Yes					
	92	Mac						
	93	Single computer station	Yes					
	94	Multiple users on network						
[illegible]								
	95	Theory of Hydrologic Processes	Yes					
	96	Assumptions and Approximations	Yes					
	97	Incorporation of User Comments	Yes					
	98	Extensive Documentation	Yes					
[illegible]								
	99	Modifiable by user	Yes, with permission					
	100	Proprietary Code	No					
[illegible]idation								
Calibration and Validation								
	101	Event-based only	No					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	No					
	104	Statistics of Observed vs Simulated Outputs	No					
	105	Automatic optimization of calibration parameters	No					
	106	Expert System	No					
[illegible]jectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel	Yes					
	108	Internal Database - Manual Input						
	109	Input via Access or other database						
	110	Import GIS Files	Yes					
	111	Import Remotely Sensed Data	Yes					
	112	Output exportable to Excel	Yes					
	113	Output exportable to GIS	Yes					
	114	Output exportable to common database						
[illegible]ry out uncertainty analyses								
Uncertainty Analysis								
	115	Monte Carlo Approach - User defined input probability distributions						
	116	Use synthesized input data series	Yes					

Table A.4 Assessment of MIKE-SHE for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	No.	Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL: MIKE-SHE	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value		How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	
Ability to Incorporate Key Features of Watershed being Modelled						
	1	Physical Characteristics such as Area, Elevation, Slope			Yes, uses area of sub-basin or grid size, average slope of sub-basin or grid, and average elevation of sub-basin or grid used for adjustment of climate data from measurement station (e.g., precipitation, air temperature) These data can be supplied into the model in grid or shape files format and as constants or time varying data Elevation (topograp	
	2	Soil/Surficial Geology			Yes; used for assigning runoff parameters to the different grids or polygons (i.e., sub-basins); the different soil types can be linked to different runoff parameters dynamically These data can be supplied into the model in grid or shape files format and as constants or time varying data.	
	3	Vegetation Type/Density			Yes; used for assigning runoff resistance, evapotranspiration (ET), and interception parameters to the different grids or polygons (i.e., sub-basins); the different vegetation type/density can be linked to different mmaning's N, ET, and interception parameters dynamically These data can be supplied into the model in grid or shape files format and as c	
	4	Aspect			Yes, respresented in terms of topography that defines the drainage surface for overland flow	
	5	Anthropogenic Changes in Land Cover			Yes; dynamic vegetation change may be included	
	6	Variable Runoff Contributing Areas (e.g. Non-contributing Areas under Average Hydrologic Conditions)			Not considered	
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled						
	7	Direct Runoff from Rain			Yes; Two methods are available (conceptual reservoir routing & 2D diffusion wave approximation).	
	8	Direct Runoff from Snowmelt			Yes, Uses temperature index method	
	9	Interflow			Yes; modeled as interflow from higher to lower interflow zone with a subcatchment (e.g., upland to floodplain within each subcatchment) Interflow reservoir is like a bathtub with one inlet and two outlets -i.e., inlet is the reservoir upstream plus net infiltration; outflow is to baseflow reservoir and the downstream interflow reservoir (or stream)	
	10	Infiltration/Groundwater			Yes; Three methods are available (2-layer water balance; 1D gravity drainage, & 1D Richards equation); if evapotranspiration is not selected/simulated, the infiltration can be specified as net rainfall fraction (i.e., fraction of rainfall that is available for infiltration and overland flow)	
	11	Interception			Yes; interception of rainfall by the canopy is modeled as a function of Leaf Area Index (LAI) and Interception Coefficient (C-int). Evaporation from the canopy is modeled as a function of LAI, C-int, and Potential Evaporation (E-pot).	
	12	Baseflow			Yes; Two methods are available (linear reservoir approach & 3D darcy flow equation)	
	13	Winter flows			No	
	14	Lake Evaporation			Yes; modeled as evaporation from ponded water or as net precipitation calcaluted offline and supplied as input data	
	15	Evapotranspiration			Yes; four methods are available (net precipitation, simple water balance approach, Kristensen and Jensen, & soil vapor atmospheric transfer)	
	16	Snow sublimation			Yes; if air temperure is below the threshold melting temperature, then the water will be removed from the snow storage as sublimation before any other ET, as E-snow = Reference-ET*deltaT where deltaT is the simulation time step	
	17	Snow transport/re-distribution			Not considered	
Ability to Simulate Processes on Event to Multi-year Basis						
	18	Event-simulation only			No	
	19	Continuous Simulation			Yes	
Ability to Simulate Key Hydraulic Features						
	20	Main Channel Routing			Yes, uses MIKE 11 where five methods are available (kinematic wave approximation, diffusive wave approximation, fully dynamic wave approximation, muskingum, & muskingum-cunge)	
	21	Routing through a Network of Channels			Yes; uses MIKE 11.	
	22	Storage in Lakes/Wetlands			Yes Simulated using specified elevation-storage-discharge relationship/function.	
	23	Floodplain Routing and Storage			Yes	
	24	Flow under Ice Cover			No	
	25	Ice jams and/or break-up			No	
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled						
	26	Watershed			Yes	
	27	Sub-basin			Yes	
	28	Local Drainage/Landscape Feature			Yes	
	29	Hillslope catchment			Yes	
	30	Lakes/Wetlands			Yes	
	31	Perched Basins			Yes	
	32	Beaver Dams			Yes	
Ability to Provide Outputs at Time Scale of Interest						
	33	Annual			Yes	
	34	Monthly			Yes	
	35	Daily			Yes	
	36	Hourly			Yes	
Ability of Model to Use Format of Downscaled Climate Data						
	37	With no or minimal pre-processing			Yes	
	38	With considerable pre-processing			No	
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements						
Climate						
	39	Temperature: Min Max Avg	Yes, average			
			Point	1-min to 1-day average		
			Grid cell	1-min to 1-day average		
			Sub-basin	1-min to 1-day average		
	40	Rain		Interval precipitation		
			Point	1-min to 1-month total		
			Grid cell	1-min to 1-month total		
			Sub-basin	1-min to 1-month total		
			Isohyets	1-min to 1-month total		
			Thiessen Polygons	1-min to 1-month total		
	41	Snow				
			Snow pillow	No		
			Average snow depth	Yes; if uniform air temperature is below the threshold melting temperature then the provided uniform precipitation will accumulate as average snow depth		
			Snow depth by land/vegetation class	Yes; if spatially variable air temperature is below the threshold melting temperature then the precipitation will accumulate as snow at different elevation/vegetation		
			Snow density	No		
			Snow water equivalent	No		
	42	Solar Radiation	yes			
			Hourly	Yes; used in Penman-Monteith method for computing reference ET		
			Daily	Yes; used in Penman-Monteith method for computing reference ET		
	43	Wind	yes			
			Hourly	Yes, used in Penman-Monteith method for computing reference ET		
			Daily	Yes; used in Penman-Monteith method for computing reference ET		
	44	Relative Humidity	Daily	Yes; used in Penman-Monteith method for computing reference ET		
	45	Cloudiness	Daily	No		
	46	Evaporation	Daily	Yes, can be computed by the model or supplied by the user as actual evaporation input data		
	47	Evapotranspiration	Daily	Yes; can be computed by the model or supplied by the user as potential evapotranspiration input data		
Discretization of Watershed						
	48	Grid cells	Yes			
	49	Sub-basins	Yes			
	50	Elevation contours	No			
	51	DEM	No			
Representation of Streams						
	52	GIS-based Hydrography	Yes, only used to develop schematized network			
	53	Conceptual Schematized Network	Yes			
	54	Storage Elements	Yes			
Geology						
	55	Surficial	Yes, can be supplied into the model in grid file, shape file, or GIS map format and as constants or time varying data. used for assigning runoff parameters to the different grids or polygons (i.e., sub-basins); the different surficiel geology types can be linked to different runoff parameters dynamically			
	56	Soil	Yes, can be supplied into the model in grid file, shape file, or GIS map format and as constants or time varying data used for assigning runoff parameters to the different grids or polygons (i.e., sub-basins); the different soil types can be linked to different runoff parameters dynamically			
Vegetation Coverage						
	57	Muskeg	Yes, Vegetation Coverage is required if Evapotranspiration is selected in the simulation specification; muskeg can be represented in terms of Leaf Area Index, root depth, and vegetation property file. There is a special of time-varying real data			
	58	Forest	Yes, Vegetation Coverage is required if Evapotranspiration is selected in the simulation specification, forest can be represented in terms of Leaf Area Index, root depth, and vegetation property file There is a special of time-varying real data.			

[illegible]		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	MIKE-SHE	
...teria and Sub-Criteria Relevant to ...jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1. Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	59	Grass	Yes, Vegetation Coverage is required if Evapotranspiration is selected in the simulation specification, grass can be represented in terms of Leaf Area Index, root depth, and vegetation property file There is a special of time-varying real data					
	60	Cleared Areas	Yes, Vegetation Coverage is required if Evapotranspiration is selected in the simulation specification, cleared areas can be represented as bare land					
[illegible] Sophistication of Processes ...mulated in Model - REGION ...EPENDENT								
[illegible]								
	61	Unit Hydrograph	No					
	62	Conceptual storages	Yes					
	63	Hydrologic Response Units	No					
	64	Water Balance	Yes					
[illegible]								
	65	Degree day	Yes					
	66	Energy Equations	No					
[illegible]								
	67	Energy Equations	No, Penman-Monteith typically the method for estimating reference ET					
	68	Morton's Approach	No, Penman-Monteith typically the method for estimating reference ET					
	69	Pan Evaporation	Yes					
[illegible]								
	70	Hydrograph Translation	Yes					
	71	Muskingum	Yes					
[illegible]								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	Yes					
[illegible]								
	74	Based on temperature	Yes					
	75	Steady rate	Yes					
[illegible]								
[illegible]								
	76	Commercial-Wide Use	Yes					
	77	Commercial-Limited Use						
	78	Public Domain-Wide Use						
	79	Public Domain-Limited Use						
	80	Research-Real World Applications						
	81	Research-Limited Application						
	82	Research-Under Development						
[illegible]								
	83	Training provided by developers	Yes					
	84	Training provided by consultants	Yes					
	85	Frequent training workshops	Yes					
	86	Help Files and Example Applications	Yes					
[illegible]								
	87	Win 95	Yes					
	88	Win 98	Yes					
	89	Win 2000	Yes					
	90	UNIX						
	91	DOS						
	92	Mac						
	93	Single computer station	Yes					
	94	Multiple users on network						
[illegible]								
	95	Theory of Hydrologic Processes	Yes					
	96	Assumptions and Approximations	Yes					
	97	Incorporation of User Comments	Yes					
	98	Extensive Documentation	Yes					
[illegible]								
	99	Modifiable by user	No					
	100	Proprietary Code	Yes					
[illegible] ...idation								
Calibration and Validation								
	101	Event-based only	No					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	Yes					
	104	Statistics of Observed vs Simulated Outputs	Yes					
	105	Automatic optimization of calibration parameters	Yes					
	106	Expert System	[illegible]					
[illegible] ...jectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel	Yes					
	108	Internal Database - Manual Input	Yes					
	109	Input via Access or other database	Yes					
	110	Import GIS Files	Yes					
	111	Import Remotely Sensed Data	Yes					
	112	Output exportable to Excel	Yes					
	113	Output exportable to GIS	Yes					
	114	Output exportable to common database	Yes					
[illegible] ...rry out uncertainty analyses								
Uncertainty Analysis								
	115	Monte Carlo Approach - User defined input probability distributions	No					
	116	Use synthesized input data series	Yes					

Table A.5 Assessment of HSPF for Hydro-Climate Modelling of Lower Athabasca Region

[illegible]		Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL: HSPF	SCORE FOR TEST MODEL
[illegible]eria and Sub-Criteria Relevant to [illegible]jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1. Adds uncertainty 0: No value		How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	
[illegible]bility to Incorporate Key Features of Watershed being Modelled						
	1	Physical Characteristics such as Area, Elevation, Slope	Perv ous land segment area and impervious land segment area are required Elevation of the land segment and of temperature gauge are required for transfering air temperature from gauging station to the subbasin Slope of the overland flow plane is required for overland flow determination			
	2	Soil/Surficial Geology	Considered in soil moisture water balance through specification of infiltration capacity, soil moisture storage, etc			
	3	Vegetation Type/Density	Pervious land segment covered by forest is required for snow to transpire (the forest can transpire through any snow cover) in winter, snow sublimation and melt, evapotranspiration, etc			
	4	Aspect	Aspect is not a factor in snowmelt routines Latitude of the pervious land segment is required when snowmelt is determined by energy balance method			
	5	Anthropogenic Changes in Land Cover	Different land uses can be considered by the model			
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)	No, but the model can be set-up using reservoirs with no outflow from non-contributing areas during average hydrologic conditions, but with outflow during flood events			
[illegible]ity to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled						
	7	Direct Runoff from Rain	Uses the Chezy-Manning equation for direct surface runoff and an empirical expression similar to Manning's equation for routing surface runoff Total direct runoff is resulted from the combination of rainfall and snow water equivalent			
	8	Direct Runoff from Snowmelt	Snowmelt runoff based on either the energy method or the temperature index method			
	9	Interflow	Interflow is separated from surface runoff and infiltration (varying with % of area) parameters Interflow outflow has non-linear relationship to interflow storage			
	10	Infiltration/Groundwater	Infiltration simulation uses probability distribution to specify areal variation and Philips equation for soil moisture Groundwater is either active or inactive groundwater storage			
	11	Interception	Interception storage (the user supplies the interception capacity on a monthly basis to account for seasonal variations, or one value designating a fixed capacity) is removed by evaporation			
	12	Baseflow	Baseflow is the groundwater outflow from the active groundwater storage and calculated using non linear equations			
	13	Winter flows	No The model does not have the capability to simulate frozen soil or flow freezing to stream bottom when the flow is very small			
	14	Lake Evaporation	Lake evaporation specified through estimates from application of Morton's model or some other approach			
	15	Evapotranspiration	Evapotranspiration is simulated as losses (up to potential ET specified by user through application of Morton's or another approach) from interception storage, active groundwater storage, exposed baseflow runoff, and from upper and lower zone soil storages			
	16	Snow sublimation	Based on a calibration sublimation parameter provided for each land use in the empirical relationship for the sublimation			
	17	Snow transport/re-d stribution	No, but calculates percent of sub-watershed covered by snow from a user-input average snow depth (user-input maximum snowpack at which the entire pervious land surface will be covered with snow)			
[illegible]ity to Simulate Processes on Event to Multi-year Basis						
	18	Event-simulation only	No			
	19	Continuous Simulation	Yes			
[illegible]ity to Simulate Key Hydraulic Features						
	20	Main Channel Routing	Yes Using storage routing			
	21	Routing through a Network of Channels	Yes Flow in reaches can be routed by storage routing.			
	22	Storage in Lakes/Wetlands	Yes			
	23	Floodplain Routing and Storage	No			
	24	Flow under Ice Cover	No			
	25	Ice jams and/or break-up	No			
[illegible]ity to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled						
	26	Watershed	Yes			
	27	Sub-basin	Yes, through user-defined discretization			
	28	Local Drainage/Landscape Feature	Yes, through user-defined discretization			
	29	Hillslope catchment	Yes, through user-defined discretization			
	30	Lakes/Wetlands	Yes, through user-defined storage elements			
	31	Perched Basins	No			
	32	Beaver Dams	No			
[illegible]ity to Provide Outputs at Time Scale of Interest						
	33	Annual	Yes			
	34	Monthly	Yes			
	35	Daily	Yes			
	36	Hourly	Yes			
[illegible]ity of Model to Use Format of Downscaled Climate Data						
	37	With no or minimal pre-processing	No			
	38	With considerable pre-process ng	Yes			
[illegible] Model's Data/Scale/Resolution Requirements						
[illegible]						
	39	Temperature: Min Max Avg				
			Point	Hourly average		
			Grid cell	No		
			Sub-basin	No		
	40	[illegible]				
			Point	Hourly or daily total (determined from hourly or daily precipitation)		
			Grid cell	No		
			Sub-basin	Yes		
			Isohyets	No		
			Thiessen Polygons	No		
	41	[illegible]				
			Snow pillow	No		
			Average snow depth	Hourly or daily total (determined from hourly or daily precipitation)		
			Snow depth by land/vegetation class	No		
			Snow density	No		
			Snow water equivalent	No		
	42	[illegible]				
			Hourly	Yes		
			Daily	Yes		
	43	[illegible]				
			Hourly	Yes		
			Daily	Yes		
	44	Relative Humidity	Daily	Yes		
	45	Cloudiness	Daily	No		
	46	Evaporation	Daily	Yes No input from the user is required		
	47	Evapotranspiration	Daily	Yes No input from the user is required		
[illegible]						
	48	Grid cells	No			
	49	Sub-basins	Yes			
	50	Elevation contours	No			
	51	DEM	No			
[illegible]						
	52	GIS-based Hydrography	No			
	53	Conceptual/Schematized Network	Yes			
	54	Storage Elements	No			
[illegible]						
	55	Surficial	No			
	56	[illegible]	Yes			
[illegible]						
	57	[illegible]	No			

[illegible]		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	HSPF	SCORE FOR TEST MODEL
[illegible] Criteria and Sub-Criteria Relevent to [illegible] ectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes					
	59	Grass	Yes					
	60	Cleared Areas	Yes					
[illegible] Sophistication of Processes [illegible] mulated in Model - REGION [illegible] EPENDENT								
Rainfall-Runoff								
	61	Unit Hydrograph	No					
	62	Conceptual storages	Yes					
	63	Hydrologic Response Units	No					
	64	Water Balance	Yes					
[illegible]								
	65	Degree day	Yes					
	66	Energy Equations	Yes					
[illegible]								
	67	Energy Equations	Yes					
	68	Morton's Approach	Yes					
	69	Pan Evaporation	No					
[illegible]								
	70	Hydrograph Translation	No					
	71	Muskingum	Yes - Storage Routing					
[illegible]								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	Yes					
[illegible]								
	74	Based on temperature	No					
	75	Steady rate	No					
[illegible]								
Model Availability								
	76	Commercial-Wide Use						
	77	Commercial-Limited Use						
	78	Public Domain-Wide Use	Yes					
	79	Public Domain-Limited Use						
	80	Research-Real World Applications						
	81	Research-Limited Application						
	82	Research-Under Development						
[illegible]								
	83	Training provided by developers						
	84	Training provided by consultants						
	85	Frequent training workshops						
	86	Help Files and Example Applications	Yes					
Operating System								
	87	Win 95	Yes					
	88	Win 98	Yes					
	89	Win 2000	Yes					
	90	UNIX	Yes					
	91	DOS	Yes					
	92	Mac						
	93	Single computer station	Yes					
	94	Multiple users on network						
[illegible]								
	95	Theory of Hydrologic Processes	Yes					
	96	Assumptions and Approximations	Yes					
	97	Incorporation of User Comments	Yes					
	98	Extensive Documentation	Yes					
[illegible]								
	99	Modifiable by user	Yes					
	100	Proprietary Code	No					
[illegible] idation								
Calibration and Validation								
	101	Event-based only	Yes					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	Yes					
	104	Statistics of Observed vs Simulated Outputs	Yes					
	105	Automatic optimization of calibration parameters	No					
	106	Expert System	Yes					
[illegible] bjectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel	No					
	108	Internal Database - Manual Input	Yes					
	109	Input via Access or other database	Yes					
	110	Import GIS Files	No					
	111	Import Remotely Sensed Data	No					
	112	Output exportable to Excel	No					
	113	Output exportable to GIS	No					
	114	Output exportable to common database	No					
[illegible] arry out uncertainty analyses								
Uncertainty Analysis								
	115	Monte Carlo Approach - User defined input probability distributions	No					
	116	Use synthesized input data series	Yes					

Table A.6 Assessment of HEC-HMS for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	No.	Sub-Criterion	IMPORTANCE / MODEL: HEC-HMS	DATA AVAILABILITY	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value / How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated		SCORE FOR TEST MODEL
Ability to Incorporate Key Features of Watershed being Modelled					
	1	Physical Characteristics such as Area, Elevation, Slope	Incorporates sub-basin drainage area explicitly; average slope is incorporated implicitly through Lag time/time of concentration; and elevation is used to represent elevation bands in a snow melt model (i.e., subbasin with very little vs. large terrain/elevation variation)		
	2	Soil/Surficial Geology	Incorporated implicitly through selection of parameters (e.g., SCS Curve Number)		
	3	Vegetation Type/Density	Incorporated implicitly through selection of parameters (e.g., flow roughness (N), SCS Curve Number --> Initial Abstraction)		
	4	Aspect	Not considered; however, the location of a precipitation gage can be specified using latitude and longitude; only the inverse distance precipitation method requires the location of each gage to be specified to determine closeness to one or more nodes specified in each subbasin		
	5	Anthropogenic Changes in Land Cover	Not dynamically considered; however, can be incorporated implicitly through selection of parameters (e.g., flow roughness (N), SCS Curve Number --> Initial Abstraction)		
	6	Variable Runoff Contributing Areas (e.g. Non-contributing Areas under Average Hydrologic Conditions)	Not considered		
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled					
	7	Direct Runoff from Rain	Uses different methods for direct surface runoff (e.g., kinematic wave, unit hydrograph, and ModClark model that explicitly account for translation and storage)		
	8	Direct Runoff from Snowmelt	Uses temperature index method - an extension of the degree-day approach to modeling a snowpack. A typical approach to the degree day is to have a fixed amount of snowmelt for each degree above freezing.		
	9	Interflow	Not explicitly simulated; implicitly incorporated into the direct runoff		
	10	Infiltration/Groundwater	Not explicitly simulated, implicitly incorporated into baselow		
	11	Interception	Explicitly incorporated if soil moisture accounting loss method is used		
	12	Baseflow	Uses different methods for baseflow simulation (e.g., linear reservoir, recession, bounded recession, and constant monthly)		
	13	Winter flows	No		
	14	Lake Evaporation	Based on lake evaporation determined by Morton's model outside of model, i.e., user-specified		
	15	Evapotranspiration	Simulated using different methods (e.g., Green and Ampt, Soil moisture accounting (SMA), Initial and constant-rate, SCS curve number (CN), and Deficit and constant rate)		
	16	Snow sublimation	Not considered		
	17	Snow transport/re-distribution	Not considered		
Ability to Simulate Processes on Event to Multi-year Basis					
	18	Event-simulation only	Yes		
	19	Continuous Simulation	Yes		
Ability to Simulate Key Hydraulic Features					
	20	Main Channel Routing	Yes. Various methods for channel routing are available (e.g., kinematic wave, muskingum, muskingum-cunge, and Lag)		
	21	Routing through a Network of Channels	Yes. Flow in reaches can be routed using various methods (e.g., kinematic wave, muskingum, muskingum-cunge, and Lag).		
	22	Storage in Lakes/Wetlands	Yes. Simulated using specified elevation-storage-discharge relationship/function		
	23	Floodplain Routing and Storage	No		
	24	Flow under Ice Cover	No		
	25	Ice jams and/or break-up	No		
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled					
	26	Watershed	Yes		
	27	Sub-basin	Yes		
	28	Local Drainage/Landscape Feature	Yes		
	29	Hillslope catchment	Yes		
	30	Lakes/Wetlands	Yes		
	31	Perched Basins	No		
	32	Beaver Dams	No		
Ability to Provide Outputs at Time Scale of Interest					
	33	Annual	No, computation time step (ranges from 1 minute to 1 day) = output time step; annual outputs need to be aggregated offline		
	34	Monthly	No, computation time step (ranges from 1 minute to 1 day) = output time step; monthly outputs need to be aggregated offline		
	35	Daily	Yes		
	36	Hourly	Yes		
Ability of Model to Use Format of Downscaled Climate Data					
	37	With no or minimal pre-processing	Yes		
	38	With considerable pre-processing	No		
[illegible] Model's Data/Scale/Resolution Requirements					
Climate					
	39	**Temperature: Min Max Avg**	**Yes, average**		
			Point	1-min to 1-day average	
			Grid cell	1-min to 1-day average	
			Sub-basin	1-min to 1-day average	
	40	[illegible]		**Interval precipitation**	
			Point	1-min to 1-day total	
			Grid cell	1-min to 1-day total	
			Sub-basin	1-min to 1-day total	
			Isohyets	No	
			Thiessen Polygons	No	
	41	[illegible]			
			Snow pillow	No	
			Average snow depth	No	
			Snow depth by land/vegetation class	Snow depth by elevation bands	
			Snow density	No	
			Snow water equivalent	No	
	42	[illegible]			
			Hourly	Yes	
			Daily	Yes	
	43	[illegible]	**yes**		
			Hourly	No	
			Daily	No	
	44	Relative Humidity	Daily	No	
	45	Cloudiness	Daily	No	
	46	Evaporation	Daily	No, takes monthly averages	
	47	Evapotranspiration	Daily	No; takes monthly averages	
[illegible]					
	48	Grid cells	No		
	49	Sub-basins	Yes		
	50	Elevation contours	Yes		
	51	DEM	No		
[illegible]					
	52	GIS-based Hydrography	No		
	53	Conceptual Schematized Network	Yes		
	54	Storage Elements	Yes		
[illegible]					
	55	Surficial	Yes		
	56	[illegible]	Yes		
[illegible]					
	57	Muskeg	Yes		
	58	Forest	Yes		

[illegible]

Criterion		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL HEC-HMS	SCORE FOR TEST MODEL
...teria and Sub-Criteria Relevant to ...jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4 Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value			How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	59	Grass	Yes				
	60	Cleared Areas	Yes				
...of Sophistication of Processes ...imulated in Model - REGION ...EPENDENT							
Rainfall-Runoff							
	61	Unit Hydrograph	Yes				
	62	Conceptual storages	Yes				
	63	Hydrologic Response Units	No				
	64	Water Balance	No				
Snowmelt-Runoff							
	65	Degree day	Yes				
	66	Energy Equations	No				
Evaporation/Evapotranspiration							
	67	Energy Equations	No				
	68	Morton's Approach	No; uses Priestley-Taylor method OR monthly averages that can be computed using morton's approach offline				
	69	Pan Evaporation	Yes				
Routing in Stream Reaches							
	70	Hydrograph Translation	Yes				
	71	Muskingum	Yes				
Infiltration							
	72	Physics-based Spatial and Temporal Distribution	Yes				
	73	Average based on soil type	Yes				
Baseflow							
	74	Based on temperature	Yes				
	75	Steady rate	Yes				
Model Availability							
	76	Commercial-Wide Use					
	77	Commercial-Limited Use					
	78	Public Domain-Wide Use	Yes				
	79	Public Domain-Limited Use					
	80	Research-Real World Applications					
	81	Research-Limited Application					
	82	Research-Under Development					
Training/Support							
	83	Training provided by developers					
	84	Training provided by consultants					
	85	Frequent training workshops					
	86	Help Files and Example Applications	Yes				
Operating System							
	87	Win 95	Yes				
	88	Win 98	Yes				
	89	Win 2000	Yes				
	90	UNIX					
	91	DOS					
	92	Mac					
	93	Single computer station	Yes				
	94	Multiple users on network					
Description of Model's Modules							
	95	Theory of Hydrologic Processes	Yes				
	96	Assumptions and Approximations	Yes				
	97	Incorporation of User Comments	No				
	98	Extensive Documentation	Yes				
Modification of Model by User							
	99	Modifiable by user	No				
	100	Proprietary Code	Yes				
...alidation							
Calibration and Validation							
	101	Event-based only	No				
	102	Continuous-simulation	Yes				
	103	Graphics of Observed vs Simulated Outputs	Yes				
	104	Statistics of Observed vs Simulated Outputs	Yes				
	105	Automatic optimization of calibration parameters	Yes				
	106	Expert System	Yes				
...bjectives							
Compatibility of Data Management in Model with User's System							
	107	Input via Excel					
	108	Internal Database - Manual Input	Yes				
	109	Input via Access or other database	Yes; imports HEC-1 files				
	110	Import GIS Files					
	111	Import Remotely Sensed Data					
	112	Output exportable to Excel	Exports a text file that can be easily opened in Excel				
	113	Output exportable to GIS					
	114	Output exportable to common database					
...arry out uncertainty analyses							
Uncertainty Analysis							
	115	Monte Carlo Approach - User defined input probability distributions	No				
	116	Use synthesized input data series	Yes				

Table A.7 Assessment of HYDROTEL for Hydro-Climate Modelling of Lower Athabasca Region

Criteria	No.	Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	HYDROTEL	
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4. Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
Ability to Incorporate Key Features of Watershed being Modelled								
	1	Physical Characteristics such as Area, Elevation, Slope	Digital elevation model (DEM) and digitized river network are required for defining drainage structure of a basin including the river network in plain areas, and lake and reservoir areas Basin area, small sub-basins and (Relatively Homogeneous Hydrological Units) corresponding to each river reach are determined using the drainage paths from cell to cell Slope is used in the snowmelt model					
	2	Soil/Surficial Geology	The main soil type on each Relatively Homogeneous Hydrological Units (RHHU) is identified by other program called PHYSITEL to be used as input by HYDROTEL from GIS data					
	3	Vegetation Type/Density	Land use classification is based on the classification of Landsat-TM images					
	4	Aspect	The aspect of each cell of the DEM is computed from the DEM and the digitized river network for defining the drainage path from each cell to one of the cells surrounding it.					
	5	Anthropogenic Changes in Land Cover	The land use classes that have significantly different hydrological effects are selected and are generally obtained by classification of a Landsat-TM image The percentage of each land use class in each Relatively Homogeneous Hydrological Units (RHHU) is computed by other program called PHYSITEL to be used by HYDROTEL					
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)	No					
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled								
	7	Direct Runoff from Rain	Uses the modified kinematic wave equation for direct surface runoff					
	8	Direct Runoff from Snowmelt	Snowmelt runoff is based on mixed degree-day-energy-budget model					
	9	Interflow	Uses the modified kinematic wave equation for subsurface surface runoff following the computation of the vertical water budget					
	10	Infiltration/Groundwater	Infiltration/groundwater is determined by the vertical water budget model called CEQUEAU model					
	11	Interception	No					
	12	Baseflow	Baseflow is determined by the vertical water budget model called CEQUEAU model					
	13	Winter flows	No					
	14	Lake Evaporation	Evaporation from lakes is also considered by the evapotranspiration model					
	15	Evapotranspiration	Any one of five methods for estimating evapotranspiration can be used Thornthwaite and Hydro-Quebec sub-models are used when only temperature data are available Penman-Monteith needs temperature, albedo, solar radiation, humidity of the air and wind Other two are Linacre and Priestley-Taylor sub-models					
	16	Snow sublimation	No					
	17	Snow transport/re-distribution	No					
Ability to Simulate Processes on Event to Multi-year Basis								
	18	Event-simulation only	No					
	19	Continuous Simulation	Yes					
Ability to Simulate Key Hydraulic Features								
	20	Main Channel Routing	Yes Using kinematic wave or diffusion wave equations					
	21	Routing through a Network of Channels	Yes Using kinematic wave or diffusion wave equations					
	22	Storage in Lakes/Wetlands	Yes Using stage-flow relationship at the outlet of the lake.					
	23	Floodplain Routing and Storage	No					
	24	Flow under Ice Cover	No					
	25	Ice jams and/or break-up	No					
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled								
	26	Watershed	Yes					
	27	Sub-basin	Yes					
	28	Local Drainage/Landscape Feature	Yes					
	29	Hillslope catchment	Hillslope hydrology is not spefically addressed					
	30	Lakes/Wetlands	Yes					
	31	Perched Basins	No					
	32	Beaver Dams	Yes					
Ability to Provide Outputs at Time Scale of Interest								
	33	Annual	No					
	34	Monthly	No					
	35	Daily	Yes					
	36	Hourly	Yes					
Ability of Model to Use Format of Downscaled Climate Data								
	37	With no or minimal pre-processing	Yes					
	38	With considerable pre-processing	No					
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements								
Climate								
	39	Temperature: Min Max Avg						
			Point	Yes				
			Grid cell	Yes				
			Sub-basin	No				
	40	Rain						
			Point	Yes, when radar data is not available				
			Grid cell	Yes, from radar				
			Sub-basin	No				
			Isohyets	No				
			Thiessen Polygons	Yes (Used for station data interpolation)				
	41	Snow						
			Snow pillow	No				
			Average snow depth	Yes, Obtained from preciptation as a function of Air Temperature				
			Snow depth by land/vegetation class	No				
			Snow density	No				
			Snow water equivalent	No				
	42	Solar Radiation						
			Hourly	Yes, depending on the type of sub model used for determination of Evapotranspiration				
			Daily	Yes, depending on the type of sub model used for determination of Evapotranspiration				
	43	Wind						
			Hourly	Yes, depending on the type of sub model used for determination of Evapotranspiration				
			Daily	Yes, depending on the type of sub model used for determination of Evapotranspiration				
	44	Relative Humidity	Daily	Yes, depending on the type of sub model used for determination of Evapotranspiration				
	45	Cloudiness	Daily	No				
	46	Evaporation	Daily	Yes Can be calculated from other data				
	47	Evapotranspiration	Daily	Yes Can be calculated from other data				
Discretization of Watershed								
	48	Grid cells	Yes					
	49	Sub-basins	Yes					
	50	Elevation contours	No					
	51	DEM	Yes					
Representation of Streams								
	52	GIS-based Hydrography	Yes					
	53	Conceptual Schematized Network	No					
	54	Storage Elements	No					
Geology								
	55	Surficial	No					
	56	Soil	Yes					
Vegetation Coverage								
	57	Muskeg	No					

Criterion		Sub-Criterion	IMPORTANCE	DATA AVAILABILITY	MODEL: HYDROTEL	
...teria and Sub-Criteria Relevant to ...jectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value		How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes			
	59	Grass	Yes			
	60	Cleared Areas	Yes			
... Sophistication of Processes ...mulated in Model - REGION ...EPENDENT						
Rainfall-Runoff						
	61	Unit Hydrograph	No			
	62	Conceptual storages	No			
	63	Hydrologic Response Units	Yes			
	64	Water Balance	Yes			
	65	Degree day	Yes			
	66	Energy Equations	Yes			
	67	Energy Equations	Yes			
	68	Morton's Approach	No			
	69	Pan Evaporation	No			
	70	Hydrograph Translation	No			
	71	Muskingum	No			
	72	Physics-based Spatial and Temporal Distribution	In the Infiltration sub-model variables and fluxes have been defined so as to represent approximately the macro-processes in action for infiltration and redistribution of soil moisture in the soil column corresponding to a RHHU			
	73	Average based on soil type	No			
	74	Based on temperature	No			
	75	Steady rate	No			
Model Availability						
	76	Commercial-Wide Use				
	77	Commercial-Limited Use				
	78	Public Domain-Wide Use				
	79	Public Domain-Limited Use	Yes			
	80	Research-Real World Applications	Yes			
	81	Research-Limited Application				
	82	Research-Under Development	Yes			
	83	Training provided by developers				
	84	Training provided by consultants				
	85	Frequent training workshops				
	86	Help Files and Example Applications	Yes			
Operating System						
	87	Win 95	Yes			
	88	Win 98	Yes			
	89	Win 2000				
	90	UNIX				
	91	DOS				
	92	Mac				
	93	Single computer station	Yes			
	94	Multiple users on network				
	95	Theory of Hydrologic Processes	Yes			
	96	Assumptions and Approximations	Yes			
	97	Incorporation of User Comments	Yes			
	98	Extensive Documentation	Yes			
	99	Modifiable by user	Yes			
	100	Proprietary Code	No			
...alidation						
Calibration and Validation						
	101	Event-based only	Yes			
	102	Continuous-simulation	Yes			
	103	Graphics of Observed vs Simulated Outputs	Yes			
	104	Statistics of Observed vs Simulated Outputs				
	105	Automatic optimization of calibration parameters				
	106	Expert System				
...bjectives						
Compatibility of Data Management in Model with User's System						
	107	Input via Excel	No			
	108	Internal Database - Manual Input				
	109	Input via Access or other database				
	110	Import GIS Files	Yes			
	111	Import Remotely Sensed Data	Yes			
	112	Output exportable to Excel				
	113	Output exportable to GIS	Yes			
	114	Output exportable to common database				
...arry out uncertainty analyses						
Uncertainty Analysis						
	115	Monte Carlo Approach - User defined input probability distributions				
	116	Use synthesized input data series				

Table A.8 Assessment of SSARR for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	Sub-Criterion		
Criteria and Sub-Criteria Relevant to Objectives of Study		How important is this criterion for intended	SSARR
Ability to Incorporate Key Features of Watershed being Modelled			
1	Physical Characteristics such as Area, Elevation, Slope		The model considers drainage area but not slope. The catchment can be divided into elevation band, and elevation is used to represent bands in a snow melt model.
2	Soil/Surficial Geology		Not considered
3	Vegetation Type/Density		Not directly, but has a simple function that simulates the interception process of vegetation. A maximum interception quantity based on the type and density of vegetation can be specified.
4	Aspect		Not considered
5	Anthropogenic Changes in Land Cover		Not considered
6	Variable Runoff Contributing Areas (e.g. Non-contributing Areas under		Not considered
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled			
7	Direct Runoff from Rain		Runoff from rainfall is calulated from empirically derived relationships of soil moisture index versus runoff percent. Input intensity can be included as a third variable.
8	Direct Runoff from Snowmelt		Snowmelt is calculated by the temperature index or energy budget approach. The model also distinguishes melt during clear weather and rain and account snowpack conditioning which accounts for the "cold content" and liquid water deficiency of the snowpack.
9	Interflow		The runoff has surface and subsurface or interflow components.
10	Infiltration/Groundwater		Not explicitly simulated; implicitly incorporated into baselow.
11	Interception		Maximum interception quantity based on the type and density of vegetation is specified by the user. A simple function in the model simulates the interception process
12	Baseflow		The base flow components are computed as the product of Base Flow Percent and Runoff Rate. Runoff that contributes to base flow is estimated as a function of the base flow infiltration index, an index of depression storage, which holds runoff available for deep percolation.
13	Winter flows		The base flow component has a longer term and shorter term components. This separation of components gives the watershed model the capability of reproducing the late summer, fall and winter groundwater recession.
14	Lake Evaporation		Not considered
15	Evapotranspiration		Potential Evapotranspiration (PET) is computed using Thornthwaite's formula converted to produce daily values. A temperature vs. Adjustments for season and latitude, elevation and rainy days are made.
16	Snow sublimation		Not considered
17	Snow transport/re-distribution		Not directly, but adjustment can be made for gauge-catch deficiency before calculating the basin weighted average precipitation, through the user-specified characteristics of the precipitation gauge.
Ability to Simulate Processes on Event to Multi-year Basis			
18	Event-simulation only		Yes
19	Continuous Simulation		Yes
Ability to Simulate Key Hydraulic Features			
20	Main Channel Routing		Yes. The program allows flexibility to determine routing coefficients which simulate downstream peaks and timing response. Channel routing can be accomplished with either a routing equation for incremental routing, or a table which specifies time of storage-discharge relationships.
21	Routing through a Network of Channels		Yes. The program allows flexibility to determine routing coefficients which simulate downstream peaks and timing response. Channel routing can be accomplished with either a routing equation for incremental routing, or a table which specifies time of storage-discharge relationships.
22	Storage in Lakes/Wetlands		Yes. Routing of natural lake is based on free-flow conditions, i.e., elevation-outflow relationships are fixed, and outflow is determined by hydraulic head. Routing is accomplished by an iterative solution of the continuity storage equation.
23	Floodplain Routing and Storage		Yes, through a "cascade of reservoirs" technique, wherein the lag and attenuation of the flood wave are simulated through successive increments of lake-type storage.
24	Flow under Ice Cover		Yes. The snow pack may be melted by snow-ground interface and groundmelt is accounted for by a month vs. groundmelt relation, and the resulting water enters the runoff simulation without being affected by the snow conditioning.
25	Ice jams and/or break-up		Not considered
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled			
26	Watershed		Yes
27	Sub-basin		Yes
28	Local Drainage/Landscape Feature		Yes
29	Hillslope catchment		No
30	Lakes/Wetlands		No
31	Perched Basins		No
32	Beaver Dams		No
Ability to Provide Outputs at Time Scale of Interest			
33	Annual		Yes
34	Monthly		Yes
35	Daily		Yes
36	Hourly		No
Ability of Model to Use Format of Downscaled Climate Data			
37	With no or minimal pre-processing		No
38	With considerable pre-processing		Yes
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements			
Climate			
39	Temperature: Min Max Avg		
		Point	1-hour to 1-day average
		Grid cell	No
		Sub-basin	1-hour to 1-day average
40	Rain		
		Point	1-hour to 1-day average
		Grid cell	No
		Sub-basin	1-hour to 1-day average
		Isohyets	No
		Thiessen Polygons	Gauge weights are usually estimated with the Thiessen method, or from a ratio of normal station to normal watershed precipitation
41	Snow		
		Snow pillow	No
		Average snow depth	No
		Snow depth by	No
		Snow density	No
		Snow water equivalent	1-hour to 1-day averae. If temperature on the snowband is less than discrimination temperature, any precipitation not captured by interception adds to the snow water equivalent on the snowband.
42	Solar Radiation		
		Hourly	Yes
		Daily	Yes
43	Wind		
		Hourly	Yes
		Daily	Yes
44	Relative Humidity	Daily	Yes. It is calculated from Temperature and Dew Point Temperature
45	Cloudiness	Daily	Yes, through Insolation
46	Evaporation	Daily	No
47	Evapotranspiration	Daily	Yes
Discretization of Watershed			
48	Grid cells		No
49	Sub-basins		Yes
50	Elevation contours		Yes
51	DEM		No
Representation of Streams			
52	GIS-based Hydrography		No
53	Conceptual/Schematized Network		Yes

[illegible]	Sub-Criterion		
54	Storage Elements		Yes
Geology			
55	Surficial		No
56	Soil		No
Vegetation Coverage			
57	Muskeg		No
58	Forest		Not directly but interception is quantified by the user based on the type and density of vegetation.
59	Grass		No
60	Cleared Areas		No
Criteria and Sub-Criteria for Degree of Sophistication of Processes Simulated in Model REGION DEPENDENT			
Rainfall-Runoff			
61	Unit Hydrograph		No
62	Conceptual storages		Yes
63	Hydrologic Response Units		No
64	Water Balance		No
Snowmelt-Runoff			
65	Degree day		Yes
66	Energy Equations		Yes
Evaporation/Evapotranspiration			
67	Energy Equations		No
68	Morton's Approach		No. Uses Thornthwaite's formula
69	Pan Evaporation		No
Routing in Stream Reaches			
70	Hydrograph Translation		Yes
71	Muskingum		Yes
Infiltration			
72	Physics-based: Spatial and Temporal Distribution		No
73	Average based on soil type		No
Glacier-melt			
74	Based on temperature		No
75	Steady rate		No
Criteria Defining Ease of Use by Modeler			
Model Availability			
76	Commercial-Wide Use		
77	Commercial-Limited Use		
78	Public Domain-Wide Use		Yes
79	Public Domain-Limited Use		
80	Research-Real World Applications		
81	Research-Limited Application		
82	Research-Under Development		
Training/Support			
83	Training provided by developers		
84	Training provided by consultants		
85	Frequent training workshops		
86	Help Files and Example Applications		No
Operating System			
87	Win 95		Yes
88	Win 98		Yes
89	Win 2000		Yes
90	UNIX		
91	DOS		Yes
92	Mac		
93	Single computer station		Yes
94	Multiple users on network		Yes
Description of Model's Modules			
95	Theory of Hydrologic Processes		Yes, but limited
96	Assumptions and Approximations		Yes, but limited
97	Incorporation of User Comments		No
98	Extensive Documentation		Yes
Modification of Model by User			
99	Modifiable by user		Yes
100	Proprietary Code		Yes
[illegible]			
Calibration and Validation			
101	Event-based only		No
102	Continuous-simulation		Yes
103	Graphics of Observed vs Simulated Outputs		No
104	Statistics of Observed vs Simulated Outputs		Yes
105	Automatic optimization of calibration parameters		No
106	Expert System		No
Criteria Defining Data Management Objectives			
Compatibility of Data Management in Model with User's System			
107	Input via Excel		No
108	Internal Database - Manual Input		Yes
109	Input via Access or other database		Yes
110	Import GIS Files		No
111	Import Remotely Sensed Data		No
112	Output exportable to Excel		Yes
113	Output exportable to GIS		No
114	Output exportable to common database		Yes
Criteria Defining Model's Ability to carry out uncertainty analyses			
Uncertainty Analysis			
115	Monte Carlo Approach - User defined input probability distributions		No
116	Use synthesized input data series		Yes

Table A.9 Assessment of DPHM-RS for Hydro-Climate Modelling of Lower Athabasca Region

Criteria and Sub-Criteria Relevant to Objectives of Study	No.	Sub-Criterion	IMPORTANCE: How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1 Adds uncertainty 0: No value		DATA AVAILABILITY	MODEL: DPHM-RS — How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
Ability to Incorporate Key Features of Watershed being Modelled							
	1	Physical Characteristics such as Area, Elevation, Slope	Percent of area for each land cover in each basin is used to evaluate hydrologic processes at point scale and then aggregated according to the proportions of the land cover present within the sub-basin Elevation at DTED or DEM resolution, aspect (flow direction) and slope of each grid used to delinate drainage network, sub-basins and to develop response function for each sub-basin In addition, Elevation, slope and aspect used to derive topographic-soil index that is required for groundwater simulation				
	2	Soil/Surficial Geology	Spatial distribution of soil types, soil hydraulic properties are required to evaluate soil moisture water balance using Philip Equation				
	3	Vegetation Type/Density	Hydrologic processes are evaluated for different land covers at point scale and then aggregated according to the proportions of the land cover present within the sub-basin				
	4	Aspect	Elevation at DTED or DEM resolution, aspect (flow direction) and slope of each grid used to delinate drainage network, sub-basins and to develop response function for each sub-basin In addition, Elevation, slope and aspect used to derive topographic-soil index that is required groundwater simulation				
	5	Anthropogenic Changes in Land Cover	Different land uses can be considered by the model				
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)	No, but model can be setup in such a way that runoff is possible during flood events from non-contributing areas using appropriate response functions				
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled							
	7	Direct Runoff from Rain	Uses response function developed for each sub-basin using the kinematic wave equation				
	8	Direct Runoff from Snowmelt	Snowmelt runoff based on either energy method or temperature index method				
	9	Interflow	No explicit method to simulate interflow Interflow is aggregated with surface runoff				
	10	Infiltration/Groundwater	Infiltration is calculated using Philip equation by assuming active layer soil moisture, transmission zone and groundwater storage				
	11	Interception	Water balance for canopy is described using Rutter equation Interception storage is removed by evaporation, canopy storage varies with LAI				
	12	Baseflow	Baseflow determined by topographic-soil index approach developed by Sivapalan et al (1987)				
	13	Winter flows	No				
	14	Lake Evaporation	Based on lake evaporation determined using Energy Balance				
	15	Evapotranspiration	Evapotranspiration is simulated using the two-source model of Shuttleworth and Gurney (1990) based on the energy at three layers				
	16	Snow sublimation	It is based on energy available (latent heat and sensible heat exchange) for each landuse				
	17	Snow transport/re-distribution	No				
Ability to Simulate Processes on Event to Multi-year Basis							
	18	Event-simulation only	No				
	19	Continuous Simulation	Yes				
Ability to Simulate Key Hydraulic Features							
	20	Main Channel Routing	Yes Using Muskingum-Cunge flow routing method				
	21	Routing through a Network of Channels	Yes Flow in any reaches can be routed by Muskingum-Cunge method				
	22	Storage in Lakes/Wetlands	Yes - using level-pool routing				
	23	Floodplain Routing and Storage	No				
	24	Flow under Ice Cover	No				
	25	Ice jams and/or break-up	No				
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled							
	26	Watershed	Yes				
	27	Sub-basin	Yes				
	28	Local Drainage/Landscape Feature	Yes				
	29	Hillslope catchment	Yes				
	30	Lakes/Wetlands	Yes				
	31	Perched Basins	No				
	32	Beaver Dams	No				
Ability to Provide Outputs at Time Scale of Interest							
	33	Annual	Yes				
	34	Monthly	Yes				
	35	Daily	Yes				
	36	Hourly	Yes				
Ability of Model to Use Format of Downscaled Climate Data							
	37	With no or minimal pre-processing	No				
	38	With considerable pre-processing	Yes				
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements							
Climate							
	39	**Temperature: Min Max Avg**					
			Point	Hourly average			
			Grid cell	No			
			Sub-basin	Yes			
	40	**Rain**					
			Point	Hourly total			
			Grid cell	No			
			Sub-basin	Yes			
			Isohyets	No			
			Thiessen Polygons	No			
	41	**Snow**		**Hourly/Daily total**			
			Snow pillow	Yes (for model validation)			
			Average snow depth	Yes (for model validation)			
			Snow depth by land/vegetation class	Yes (for model validation)			
			Snow density	Yes			
			Snow water equivalent	Yes (for model vali			
	42	**Solar Radiation**					
			Hourly	Yes			
			Daily	No			
	43	**Wind**					
			Hourly	Hourly average			
			Daily	Daily average			
	44	Relative Humidity	Daily	Yes, hourly input possible			
	45	Cloudiness	Daily	Yes, hourly input possible, may be substitute for sunshine hours			
	46	Evaporation	Daily	No Calculated by model from other data internally			
	47	Evapotranspiration	Daily	No Calculated by model from other data internally			
Parameterization of Watershed							
	48	Grid cells	Yes				
	49	Sub-basins	Yes				
	50	Elevation contours	No				
	51	DEM	Yes				
Representation of Streams							
	52	GIS-based Hydrography	Yes				
	53	Conceptual/Schematized Network	Yes				
	54	Storage Elements	Yes				
Geology							
	55	Surficial	No				
	56	Soil	Yes				
Vegetation Coverage							
	57	Muskeg	No				

Criterion		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	DPHM-RS	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1 Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes					
	59	Grass	Yes					
	60	Cleared Areas	Yes					
Criteria and Sub-Criteria for Degree of Sophistication of Processes Simulated in Model - REGION DEPENDENT								
Rainfall-Runoff								
	61	Unit Hydrograph	No					
	62	Conceptual storages	No					
	63	Hydrologic Response Units	Yes					
	64	Water Balance	Yes					
Snowmelt-Runoff								
	65	Degree day	Yes					
	66	Energy Equations	Yes					
Evaporation/Evapotranspiration								
	67	Energy Equations	Yes					
	68	Morton's Approach	No					
	69	Pan Evaporation	No					
Routing in Stream Reaches								
	70	Hydrograph Translation	No					
	71	Muskingum	Yes - Using Muskingum-Cunge method					
Infiltration								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	Yes					
Glacier-melt								
	74	Based on temperature	No					
	75	Steady rate	No					
Criteria Defining Ease of Use by Model								
Model Availability								
	76	Commercial-Wide Use						
	77	Commercial-Limited Use						
	78	Public Domain-Wide Use						
	79	Public Domain-Limited Use						
	80	Research-Real World Applications						
	81	Research-Limited Application	Yes					
	82	Research-Under Development						
Training/Support								
	83	Training provided by developers	No					
	84	Training provided by consultants	No					
	85	Frequent training workshops	No					
	86	Help Files and Example Applications	No					
Operating System								
	87	Win 95						
	88	Win 98						
	89	Win 2000						
	90	UNIX						
	91	DOS	Yes					
	92	Mac						
	93	Single computer station	Yes					
	94	Multiple users on network						
Description of Model's Modules								
	95	Theory of Hydrologic Processes	Yes					
	96	Assumptions and Approximations	Yes					
	97	Incorporation of User Comments	Yes					
	98	Extensive Documentation	No					
Modification of Model by User								
	99	Modifiable by user	Yes					
	100	Proprietary Code	No					
Criteria for Model Calibration and Validation								
Calibration and Validation								
	101	Event-based only	No					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	No					
	104	Statistics of Observed vs Simulated Outputs	No					
	105	Automatic optimization of calibration parameters	No					
	106	Expert System	No					
Criteria Defining Data Management Objectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel	Yes					
	108	Internal Database - Manual Input						
	109	Input via Access or other database						
	110	Import GIS Files	Yes					
	111	Import Remotely Sensed Data	Yes					
	112	Output exportable to Excel	Yes					
	113	Output exportable to GIS	Yes					
	114	Output exportable to common database						
Criteria Defining Model's Ability to carry out uncertainty analyses								
Uncertainty Analysis								
	115	Monte Carlo Approach - User defined input probability distributions						
	116	Use synthesized input data series	Yes					

Table A.10 Assessment of VIC for Hydro-Climate Modelling of Lower Athabasca Region

Criteria	No.	Sub-Criterion	IMPORTANCE	DATA AVAILABILITY / MODEL: VIC	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5. Critical 4. Required but can make exception 3: Desirable 2: Can be useful 1: Adds uncertainty 0: No value	How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
Ability to Incorporate Key Features of Watershed being Modelled					
	1	Physical Characteristics such as Area, Elevation, Slope	Basin boundaries are required for determining the total area of the basin from different sources like atlas maps, digital scanned basin boundaries and digital elevation models (DEMs) Area of grid cells, average elevation of the grid cells and direction of the flow in the grid cells are rqured for flow		
	2	Soil/Surficial Geology	Different soil characteristics associated with each grid cell are considered by the model, in which they are represented with sets of soil parameters		
	3	Vegetation Type/Density	Different vegetation characteristics (represented by sets of parameters for vegetation types) in each grid cell are considered by the model. Lakes are included in the mosaic representation of grid cell vegetation classes Number of vegetation types in a grid cell and fraction of grid cell covered by vegetation type are required		
	4	Aspect	Latitude and longitude of the grid cells are needed		
	5	Anthropogenic Changes in Land Cover	Land coverage classes (vegetation, bare soil, lakes, etc) as the percentage in each grid are considered by the model		
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)			
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled					
	7	Direct Runoff from Rain	Within each vegetation class, runoff generation and spatial variability of infiltration are simulated using the variable infiltration curve The model transports grid cell surface runoff and baseflow produced within each grid cell to the outlet of that grid cell by routing and using a Unit Hydrograph approach		
	8	Direct Runoff from Snowmelt	Ground snow accumulation, sublimation and melt are simulated using a two-layer surface energy balance model		
	9	Interflow	No interflow It is combined with surface runoff		
	10	Infiltration/Groundwater	Within each vegetation class, spatial variability of infiltration and runoff generation is simulated using the variable infiltration curve Infiltration uses infiltration parameter that is adjusted during the calibration of the model and is used to describe the Variable Infiltration Curve		
	11	Interception	Interception is determined by interception capacity of the vegetation canopy which is a linear function of leaf area index (LAI) and lost by evaporation Snow intercepted in the canopy is determined by the canopy energy balance method		
	12	Baseflow	Baseflow is represented using the empirically based baseflow curve as a function of soil moisture The non-linear baseflow occurrence is controlled by soil parameters that are adjusted during the calibration of the VIC model		
	13	Winter flows	Uses frozen soil algorithm to model frozen and unfrozen layers within the soil column and frozen layer ice content		
	14	Lake Evaporation	Evaporation from the lake is obtained from surface energy balance method		
	15	Evapotranspiration	Evapotranspiration can be estimated by energy balance method and is simulated from vegetation canopy, vegetation and baresoil.		
	16	Snow sublimation	Sublimation is simulated from a two-layer surface energy balance model and from sNow transport algorithm		
	17	Snow transport/re-distribution	Snow transport is determined by snow transport and blowing snow sublimation algorithm		
Ability to Simulate Processes on Event to Multi-year Basis					
	18	Event-simulation only	No		
	19	Continuous Simulation	Yes		
Ability to Simulate Key Hydraulic Features					
	20	Main Channel Routing	Main channel routing uses the linearized Saint-Venant equation		
	21	Routing through a Network of Channels	For network of channels routing, flow direction file is required that tells the routing model how all of the grid cells are connected in the routing network Channel routing uses the linearized Saint-Venant equation.		
	22	Storage in Lakes/Wetlands	Yes		
	23	Floodplain Routing and Storage	No		
	24	Flow under Ice Cover	No		
	25	Ice jams and/or break-up	No		
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled					
	26	Watershed	Yes		
	27	Sub-basin	Yes		
	28	Local Drainage/Landscape Feature	Yes		
	29	Hillslope catchment	No		
	30	Lakes/Wetlands	Yes		
	31	Perched Basins	No		
	32	Beaver Dams	No		
Ability to Provide Outputs at Time Scale of Interest					
	33	Annual	No		
	34	Monthly	No		
	35	Daily	Yes		
	36	Hourly	Yes		
Ability of Model to Use Format of Downscaled Climate Data					
	37	With No or minimal pre-processing	No		
	38	With considerable pre-processing	Yes		
Model's Data/Scale/Resolution Requirements					
Climate					
	39	**Temperature: Min Max Avg**	**Min & Max**		
			Point	Yes Daily or sub-daily	
			Grid cell	Yes Daily or sub-daily	
			Sub-basin	No	
	40	**Rain**	**obtained from precipitation**		
			Point	Yes	
			Grid cell	Yes	
			Sub-basin	No	
			Isohyets	No	
			Thiessen Polygons	No	
	41	**Snow**	**precipitation occurring below a threshold temperature is assumed to be snow**		
			Snow pillow	No	
			Average sNow depth	Yes	
			Snow depth by land/vegetation class	No	
			Snow density	No	
			Snow water equivalent	No	
	42	**Solar Radiation**			
			Hourly	Yes (optional)	
			Daily	Yes (optional)	
	43	**Wind**			
			Hourly	Yes (optional)	
			Daily	Yes (optional)	
	44	Relative Humidity	Daily	Yes (optional)	
	45	Cloudiness	Daily	No	
	46	Evaporation	Daily	Yes But can be calculated from other data	
	47	Evapotranspiration	Daily	Yes But can be calculated from other data	
Discretization of Watershed					
	48	Grid cells	Yes		
	49	Sub-basins	No		
	50	Elevation contours	No		
	51	DEM	Yes Using Arc/Info GIS		
Representation of Streams					
	52	GIS-based Hydrography	Yes		
	53	Conceptual/Schematized Network	No		
	54	Storage Elements	No		
Geology					
	55	Surficial	No		
	56	Soil	Yes		
Vegetation Coverage					
	57	Muskeg	No		

[illegible]		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL	VIC	
[illegible]teria and Sub-Criteria Relevant to [illegible]jectives of Study			How important is this criterion for intended objectives ? 5. Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1. Adds uncertainty 0: No value				How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	SCORE FOR TEST MODEL
	58	Forest	Yes					
	59	Grass	Yes					
	60	Cleared Areas	Yes					
[illegible] Sophistication of Processes [illegible]mulated in Model - REGION [illegible]EPENDENT								
Rainfall-Runoff								
	61	Unit Hydrograph	Yes For routing generated flow to the edge of the gridcell					
	62	Conceptual storages	No					
	63	Hydrologic Response Units	No					
	64	Water Balance	Yes					
[illegible]								
	65	Degree day	No					
	66	Energy Equations	Yes					
[illegible]								
	67	Energy Equations	Yes					
	68	Morton's Approach	No					
	69	Pan Evaporation	No					
[illegible]								
	70	Hydrograph Translation	No Uses the linearized Saint-Venant equation					
	71	Musk ngum	No					
[illegible]								
	72	Physics-based Spatial and Temporal Distribution	Yes					
	73	Average based on soil type	No					
[illegible]								
	74	Based on temperature	No					
	75	Steady rate	No					
[illegible]								
Model Availability								
	76	Commercial-Wide Use	No					
	77	Commercial-Limited Use	No					
	78	Public Domain-Wide Use	No					
	79	Public Domain-Limited Use	No					
	80	Research-Real World Applications	Yes					
	81	Research-Limited Application	Yes					
	82	Research-Under Development	Yes					
[illegible]								
	83	Training provided by developers						
	84	Training provided by consultants						
	85	Frequent training workshops						
	86	Help Files and Example Applications	Yes					
[illegible]								
	87	Win 95	No					
	88	Win 98	No					
	89	Win 2000	No					
	90	UNIX	Yes					
	91	DOS	Yes					
	92	Mac	No					
	93	Single computer station						
	94	Multiple users on network						
[illegible]								
	95	Theory of Hydrologic Processes	Yes					
	96	Assumptions and Approximations	Yes					
	97	Incorporation of User Comments	Yes					
	98	Extensive Documentation	Yes					
[illegible]								
	99	Modifiable by user	Yes					
	100	Proprietary Code	No					
[illegible]idation								
Calibration and Validation								
	101	Event-based only	No					
	102	Continuous-simulation	Yes					
	103	Graphics of Observed vs Simulated Outputs	Yes					
	104	Statistics of Observed vs Simulated Outputs	No					
	105	Automatic optimization of calibration parameters	Yes					
	106	Expert System	No					
[illegible]bjectives								
Compatibility of Data Management in Model with User's System								
	107	Input via Excel	No					
	108	Internal Database - Manual Input	Yes Using ascii format for parameter files					
	109	Input via Access or other database	No					
	110	Import GIS Files	Yes Using Arc/Info GIS					
	111	Import Remotely Sensed Data	No					
	112	Output exportable to Excel	No					
	113	Output exportable to GIS	No					
	114	Output exportable to common database	No					
[illegible]rry out uncertainty analyses								
Uncertainty Analysis								
	115	Monte Carlo Approach - User defined input probability distributions						
	116	Use synthesized input data series						

Table A.11 Assessment of CRHM for Hydro-Climate Modelling of Lower Athabasca Region

Criterion	No.	Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL: CRHM	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5. Critical 4: Required but can make exception 3: Desirable 2: Can be useful 1 Adds uncertainty 0: No value			How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	
Ability to Incorporate Key Features of Watershed being Modelled							
	1	Physical Characteristics such as Area, Elevation, Slope	Basin area and areas of hydrologic response units(HRUs) are required Elevations of the HRUs and stations are required for determining air pressure in the Evaporation calculation for the HRUs and other lapse rate calclations The average slope of the HRU is required for adjusting short wave radiation and wind speed for topography				
	2	Soil/Surficial Geology	Soil types of the HRUs are required for infiltration modules				
	3	Vegetation Type/Density	Vegetation height is used in snow model, and vegetation cover type of the HRUs are required for determining evaotranspiration and in soil moisture balance				
	4	Aspect	Aspect angle of the HRU is used in vertical exchange process Used in the determination of short wave radiation				
	5	Anthropogenic Changes in Land Cover	The model is sensitive to land use The HRUs are subdivisions of the basin and are characterized by the operator based on an understanding of the hydrological processes, terrain and land use Yes, we need to specify the land cover type as bare soil, crops, grasses and shrubs				
	6	Variable Runoff Contributing Areas (e g Non-contributing Areas under Average Hydrologic Conditions)	Yes				
Ability to Simulate Dominant/Key Hydrologic Processes in Watershed being Modelled							
	7	Direct Runoff from Rain	Direct surface runoff from rain is determined from infiltrarion modules and routed by lag and route method				
	8	Direct Runoff from Snowmelt	Snowmelt runoff is based on one of the following methods Energy balance snow melt by Gray and Landine, fractal snowmelt and snow cover depletion, simple land surface scheme like melt model by Essery and Etchevers, meltwater routing by Albert and Krajeski, net radiation and temperature index by Kustas et al				
	9	Interflow	Subsurface flow is determined by soil moisture balance modules and routed by lag and route method				
	10	Infiltration/Groundwater	Variety of infiltration routines for frozen soils, basic method from Granger, parametric method from Gray . frost depth calculation, simple unfrozen soil infiltration, Green-Ampt infiltration and redistribution by Ogden and Saghafian. There is groundwater in the model.				
	11	Interception	Rainfall interception is calculated based on Rutter et al , and Rutter and Morton Snow interception in forest canopies based on Hedstrom and Pomeroy method				
	12	Baseflow	Baseflow is the groundwater outflow determined by soil moisture balance modules and routed by lag and route method				
	13	Winter flows	Uses snowmelt models It models frozen soils using a FROZEN SOIL INFILTRATION MODULE				
	14	Lake Evaporation	Consider water body as one of the land cover types				
	15	Evapotranspiration	Selection of routines from Penman-Monteith, Granger and Pomeroy, and Shuttleworth and Wallace for determination of evapotranspiration, which is simulated from canopy storage, recharge layer and lower soil layer				
	16	Snow sublimation	Sublimation from snow interception is determined from interception modules, and sublimation from snow transport is determined from blowing snow transport and sublimation modules following Pomeroy and Li and simplified algorithms from Essery et al				
	17	Snow transport/re-distribution	Yes Snow transport is either detrmined by blowing snow transport and sublimation method by Pomeroy and Li or simplified algorithms from Essery et al				
Ability to Simulate Processes on Event to Multi-year Basis							
	18	Event-simulation only	No The model can simulate flow over a one year period				
	19	Continuous Simulation	Yes				
Ability to Simulate Key Hydraulic Features							
	20	Main Channel Routing	Yes Using lag and route hydrograph methods by Clark				
	21	Routing through a Network of Channels	Yes Flow in reaches can be routed by lag and route method				
	22	Storage in Lakes/Wetlands	Yes				
	23	Floodplain Routing and Storage	No				
	24	Flow under Ice Cover	No				
	25	Ice jams and/or break-up	No				
Ability to Provide Outputs at Spatial Scale of Interest within Watershed being Modelled							
	26	Watershed	Yes, for small to meduim size basins				
	27	Sub-basin	Yes				
	28	Local Drainage/Landscape Feature	Yes				
	29	Hillslope catchment	Yes				
	30	Lakes/Wetlands	Yes				
	31	Perched Basins	No				
	32	Beaver Dams	No				
Ability to Provide Outputs at Time Scale of Interest							
	33	Annual	No To obtain annual or monthly values the daily values should be exported to other data management system like Excel.				
	34	Monthly	No				
	35	Daily	Yes				
	36	Hourly	Yes				
Ability of Model to Use Format of Downscaled Climate Data							
	37	With no or minimal pre-processing	No				
	38	With considerable pre-processing	Yes				
Criteria and Sub-Criteria Defining Model's Data/Scale/Resolution Requirements							
Climate							
	39	**Temperature: Min Max Avg**					
			Point	Hourly average			
			Grid cell	No			
			Sub-basin	No			
	40	**Rain**					
			Point	Half hour, hourly/daily total			
			Grid cell	No			
			Sub-basin	No			
			Isohyets	No			
			Thiessen Polygons	No			
	41	**Snow**					
			Snow pillow	No			
			Average snow depth	Half hour, hourly/daily total			
			Snow depth by land/vegetation class	No			
			Snow density	No			
			Snow water equivalent	No			
	42	**Solar Radiation**					
			Hourly	Yes			
			Daily	Yes			
	43	**Wind**					
			Hourly	Hourly average			
			Daily	Daily average			
	44	Relative Humidity	Daily	Yes (Interval) Half hour, hourly average			
	45	Cloudiness	Daily	No			
	46	Evaporation	Daily	No			
	47	Evapotranspiration	Daily	No			
Discretization of Watershed							
	48	Grid cells	No				
	49	Sub-basins	Yes				
	50	Elevation contours	No				
	51	DEM	No But from ARCGIS				
Representation of Streams							
	52	GIS-based Hydrography	No				
	53	Conceptual/Schematized Network	Yes				
	54	Storage Elements	No				
Geology							
	55	Surficial	No				
	56	Soil	Yes				
Vegetation Coverage							
	57	Muskeg	No				
	58	Forest	Yes				

Criterion		Sub-Criterion		IMPORTANCE	DATA AVAILABILITY	MODEL: CRHM	SCORE FOR TEST MODEL
Criteria and Sub-Criteria Relevant to Objectives of Study			How important is this criterion for intended objectives ? 5: Critical 4 Required but can make exception 3 Desirable 2: Can be useful 1 Adds uncertainty 0: No value			How does the Model Address Criterion/Sub-Criterion ? 5: Very Well 4: Reasonably Well 3: Adequate 2: Would Require Some Changes in Code 1: Would Require Considerable Re-Coding 0: Not Simulated	
	59	Grass	Yes				
	60	Cleared Areas	Yes				
Criteria Defining Sub-Criteria for Degree of Sophistication of Processes Simulated in Model - REGION DEPENDENT							
Rainfall-Runoff							
	61	Unit Hydrograph	No				
	62	Conceptual storages	No				
	63	Hydrologic Response Units	Yes				
	64	Water Balance	Yes				
Snowmelt-Runoff							
	65	Degree day	Yes				
	66	Energy Equations	Yes				
Evaporation/Evapotranspiration							
	67	Energy Equations	Yes				
	68	Morton's Approach	Yes				
	69	Pan Evaporation	No				
Routing in Stream Reaches							
	70	Hydrograph Translation	No				
	71	Muskingum	Yes - lag and route method				
Infiltration							
	72	Physics-based Spatial and Temporal Distribution	Yes				
	73	Average based on soil type	Yes				
Groundwater							
	74	Based on temperature	Yes It uses two modules that calculate the ground flux for hummuck-covered hillslopes in the Artic tundra and handles the subsurface drainage from hummock-covered hillslopes in the Arctic tundra				
	75	Steady rate	No				
Criteria Defining Ease of Use of Model							
Model Availability							
	76	Commercial-Wide Use	No				
	77	Commercial-Limited Use	No				
	78	Public Domain-Wide Use	No				
	79	Public Domain-Limited Use	No				
	80	Research-Real World Applications	Yes				
	81	Research-Limited Application	Yes				
	82	Research-Under Development	Yes				
Training/Support							
	83	Training provided by developers					
	84	Training provided by consultants					
	85	Frequent training workshops	Yes				
	86	Help Files and Example Applications	Yes				
Operating System							
	87	Win 95	Yes				
	88	Win 98	Yes				
	89	Win 2000	Yes				
	90	UNIX	Yes				
	91	DOS	No				
	92	Mac	Yes				
	93	Single computer station	Yes				
	94	Multiple users on network	No				
Description of Model's Modules							
	95	Theory of Hydrologic Processes	Yes				
	96	Assumptions and Approximations	Yes				
	97	Incorporation of User Comments	Yes				
	98	Extensive Documentation	Yes				
Modification of Model by User							
	99	Modifiable by user	Yes But with the permission of the developers				
	100	Proprietary Code	No				
Criteria for Model Calibration and Validation							
Calibration and Validation			There is no internal provision for calibration. Parameters are either estimated or measured				
	101	Event-based only					
	102	Continuous-simulation					
	103	Graphics of Observed vs Simulated Outputs					
	104	Statistics of Observed vs Simulated Outputs					
	105	Automatic optimization of calibration parameters					
	106	Expert System					
Criteria Defining Data Management Objectives							
Compatibility of Data Management in Model with User's System							
	107	Input via Excel	No				
	108	Internal Database - Manual Input	Yes				
	109	Input via Access or other database	No				
	110	Import GIS Files	Yes				
	111	Import Remotely Sensed Data	No				
	112	Output exportable to Excel	Yes				
	113	Output exportable to GIS	Yes				
	114	Output exportable to common database					
Criteria Defining Model's Ability to carry out uncertainty analyses							
Uncertainty Analysis							
	115	Monte Carlo Approach - User defined input probability distributions					
	116	Use synthesized input data series					

APPENDIX B

Physical Characteristics of Athabasca River Basin and Beaver River Basin

ALBERTA
Edmonton
Calgary
N
7C
7B
9B
9A
2E
6
8
PONTON RIVER
MARGARET LAKE
WENTZEL LAKE
PEACE RIVER
CHINCHAGA RIVER
BUFFALO RIVER
WABASCA RIVER
NOTIKEWIN RIVER
CADOTTE RIVER
LOON RIVER
PEERLESS LAKE
GRAHAM LAKE
CARDINAL LAKE
UTIKUMA RIVER
UTIKUMA LAKE
MUSKWA RIVER
NORTH WABASCA LAKE
SOUTH WABASCA LAKE
LESSER SLAVE LAKE
WINAGAMI
BIRCH RIVER
MIKKWA RIVER
NAMUR LAKE
ELLS RIVER
MACKAY RIVER
CLEARWATER RIVER
GORDON LAKE
WINEFRED LAKE
RICHARDSON RIVER
BARIL LAKE
LAKE CLAIRE
MAMAWI LAKE
RICHARDSON LAKE
LAKE ATHABASCA
OLD FORT RIVER
COLIN LAKE
DOUGLAS RIVER
WILLIAM RIVER
MACFARLANE RIVER
OTHERSIDE RIVER
GREASE RIVER
MIRROR RIVER
LA LOCHE RIVER
KIMOWIN RIVER
DILLON RIVER
MUDJATIK RIVER
CHURCHILL RIVER
MCCUSKER RIVER
CANOE RIVER
07DD007
07BK007
07CA012
07CB001
07BF009
07CD004
200000
300000
400000
500000
600000
700000
800000
900000
6600000
6500000
6400000
6300000
6200000

LEGEND

- WATERCOURSE
- ATHABASCA RIVER
- CITY
- HYDROLOGIC REGION
- SUB-BASIN
- STUDY AREA
- NON-CONTRIBUTING AREA
- WATERBODY

SOIL TYPE

- IMPERVIOUS
- ORGANIC
- POORLY DRAINED CLAY LOAM
- POORLY DRAINED SAND
- POORLY DRAINED TILL
- RAPIDLY DRAINED SAND
- RAPIDLY DRAINED TILL
- WELL DRAINED CLAY LOAM
- WELL DRAINED SAND
- WELL DRAINED TILL

50 0 50

SCALE 1:2,000,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from PFRA gross drainage areas joined to selected Alberta Environment hydrometric stations and previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Surficial Geology obtained from Government of Canada / Agriculture and Agri-Food Canada(GC/AAFC). Projection: Alberta 10TM False Easting 500,000 at 115 ° W. Datum: NAD 83

PROJECT

Government of Alberta
Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

SURFICIAL GEOLOGY - ATHABASCA AND BEAVER RIVER BASINS

PROJECT NO. 08-1326-0033		SCALE AS SHOWN	REV. 0
DESIGN	OK	25 Feb. 2009	
GIS	PT	26 Jun. 2009	
CHECK	AB	05 Aug. 2009	
REVIEW	AB	05 Aug. 2009	

Golder Associates
Calgary, Alberta

FIGURE: B.1

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ALBERTA
Edmonton
Calgary
N
7C
7B
9B
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2E
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7A
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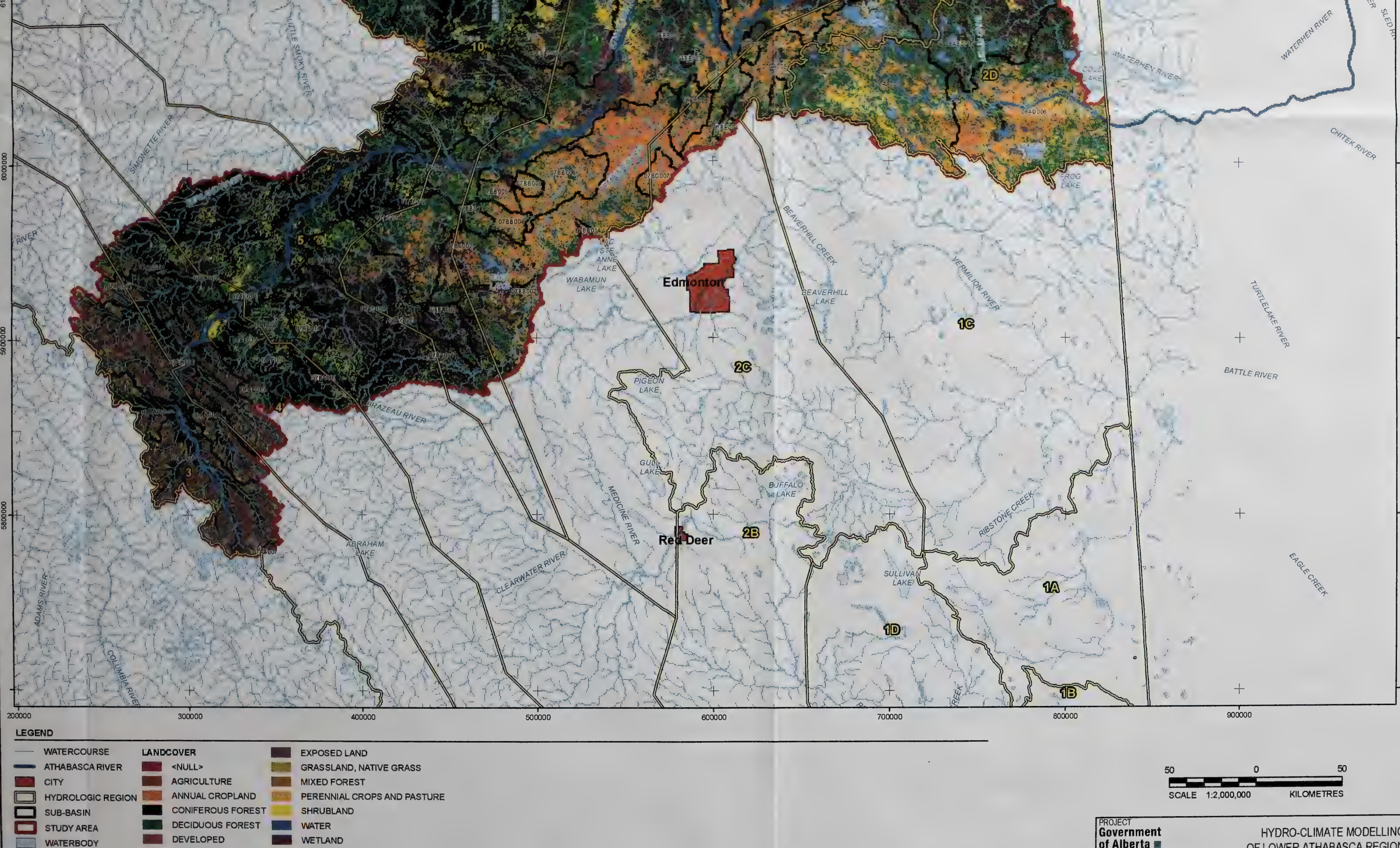
10
PONTON RIVER
MARGARET LAKE
WENTZEL LAKE
PEACE RIVER
CHINCHAGA RIVER
BARIL LAKE
LAKE ATHABASCA
MAMAWI LAKE
LAKE CLAIRE
OLD FORT RIVER
DOUGLAS RIVER
WILLIAM RIVER
MACFARLANE RIVER
OTHERSIDE RIVER
BIRCH RIVER
MIKKWA RIVER
BUFFALO RIVER
WABASCA RIVER
NOTIKEWIN RIVER
MIRROR RIVER
LOON RIVER
PEERLESS LAKE
GRAHAM LAKE
CADOTTE RIVER
CARDINAL LAKE
UTIKUMA RIVER
UTIKUMA LAKE
MUSKWA RIVER
NORTH WABASCA LAKE
SOUTH WABASCA LAKE
LA LOCHE RIVER
MUDJATIK RIVER
CHURCHILL RIVER
DILLON RIVER
MCCUSKER RIVER
CANOE RIVER
BEAVER RIVER
WATERHEN RIVER
WAPITI RIVER
STURGEON LAKE
LESSER SLAVE LAKE
CALLING LAKE



REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI. Sub-watershed areas obtained from PFRA gross drainage areas joined to selected Alberta Environment hydrometric stations and previous Golder projects. Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment. Landcover obtained from Government of Canada / Agriculture and Agri-Food Canada (GC/AAFC).
Projection: Alberta 10TM False Easting 500,000 at 115 ° W. Datum: NAD 83

PROJECT
Government of Alberta Environment
HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE
LANDCOVER - ATHABASCA AND BEAVER RIVER BASINS

Golder Associates
Calgary, Alberta

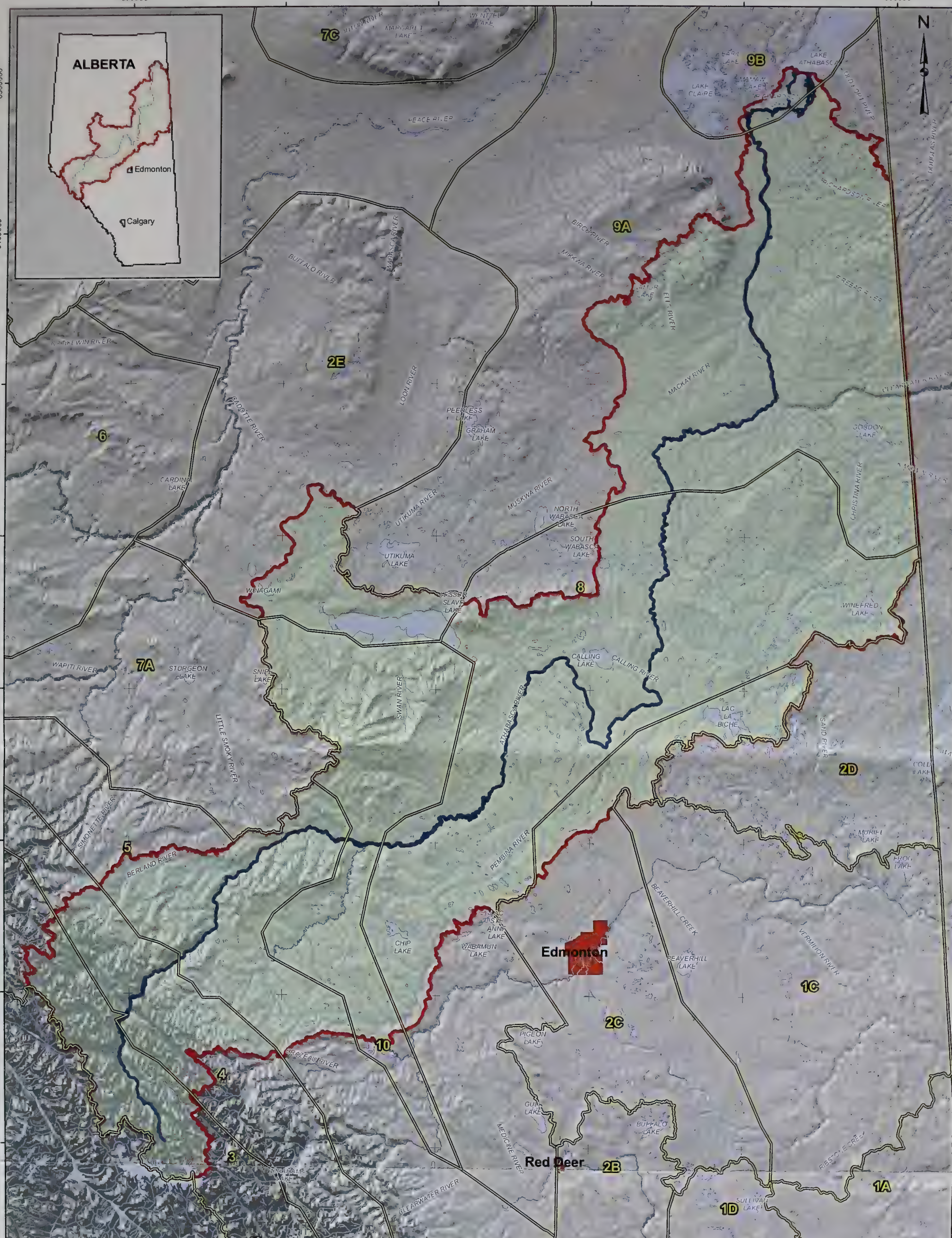
PROJECT NO. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	25 Feb. 2009		
GIS	PT	26 Jun. 2009		
CHECK	AB	05 Aug. 2009		
REVIEW	AB	05 Aug. 2009		

FIGURE: B.2

APPENDIX C

Locations of Climate and Hydrometric Stations

Golder Associates



LEGEND

- WATERCOURSE
- ATHABASCA RIVER
- HYDROLOGIC REGION
- ATHABASCA RIVER BASIN
- CITY
- WATERBODY

75 0 75

SCALE 1:2,500,000 KILOMETRES

PROJECT
Government of Alberta
Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

HYDROLOGIC REGIONS OF THE LOWER ATHABASCA REGION

Golder Associates
Calgary, Alberta

PROJECT No. 07-1326-0021			SCALE AS SHOWN	REV. 0
DESIGN	LC	11 Feb. 2008	**FIGURE: C.1**	
GIS	PT	26 Jun. 2009		
CHECK	AB	05 Aug. 2009		
REVIEW	AB	05 Aug. 2009		

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI.
Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment.
Projection: Alberta 10TM False Easting 500,000 at 115 ° W. Datum: NAD 83

ALBERTA
Edmonton
Calgary
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7C
7B
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7A
2D
PEACE RIVER
LAKE CLAIRE
RICHARDSON LAKE
RICHARDSON RIVER
BIRCH RIVER
MIKKWA RIVER
BUFFALO RIVER
NAMUR LAKE
ELLS RIVER
MACKAY RIVER
FIREBAG RIVER
CLEARWATER RIVER
GORDON LAKE
KIMOWIN RIVER
CHRISTINA RIVER
LA LOCHE RIVER
DOUGLAS RIVER
WILLIAM RIVER
MACFARLANE RIVER
MIRROR RIVER
OTHERSIDE RIVER
MUDJATIK RIVER
CHURCHILL RIVER
DILLON RIVER
MCCUSKER RIVER
BEAVER RIVER
WINEFRED LAKE
LOON RIVER
PEERLESS LAKE
GRAHAM LAKE
CARDINAL LAKE
UTIKUMA RIVER
UTIKUMA LAKE
MUSKWA RIVER
NORTH WABASCA LAKE
SOUTH WABASCA LAKE
WINAGAMI
LESSER SLAVE LAKE
CALLING LAKE
CALLING RIVER
SWAN RIVER
ATHABASCA RIVER
LAC LA BICHE
SAND RIVER
WAPITI RIVER
STURGEON LAKE

LEGEND

- ● HYDROMETRIC STATION
- WATERCOURSE
- ATHABASCA RIVER
- CITY
- HYDROLOGIC REGION
- STUDY AREA
- WATERBODY

75 0 75

SCALE 1:2,000,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI.
Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment.
Projection: Alberta 10TM False Easting 500,000 at 115 ° W. Datum: NAD 83

PROJECT
Government of Alberta
Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE
HYDROMETRIC STATIONS IN THE LOWER ATHABASCA REGION

Golder Associates
Calgary, Alberta

PROJECT NO. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	20 Feb. 2009	**FIGURE: C.2**	
GIS	PT	26 Jun. 2009		
CHECK	AB	05 Aug. 2009		
REVIEW	AB	05 Aug. 2009		

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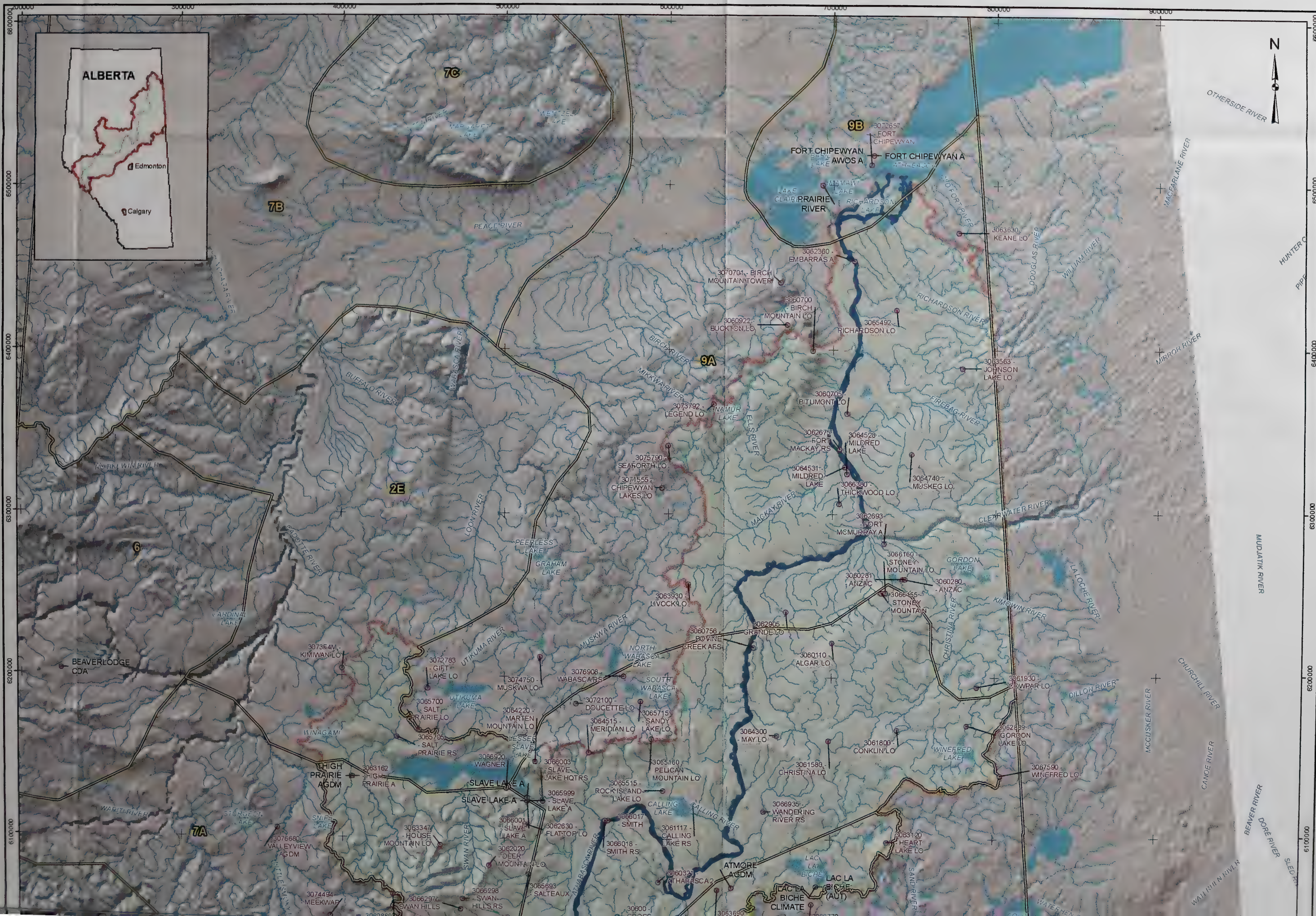

ALBERTA
Edmonton
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PEACE RIVER
BUFFALO RIVER
WABASCA RIVER
LOON RIVER
CADOTTE RIVER
BIRCH RIVER
MIKKWA RIVER
MUSKWA RIVER
UTIKUMA RIVER
SWAN RIVER
RICHARDSON RIVER
FIREBAG RIVER
MACKAY RIVER
CLEARWATER RIVER
CHRISTINA RIVER
KIMOWIN RIVER
LA LOCHE RIVER
DILLON RIVER
CHURCHILL RIVER
MCCUSKER RIVER
CANOE RIVER
BEAVER RIVER
DORÉ RIVER
MUDJATIK RIVER
WILLIAM RIVER
DOUGLAS RIVER
MACFARLANE RIVER
MIRROR RIVER
OTHERSIDE RIVER
CALLING RIVER
WAPITI RIVER
SANDY RIVER
PEERLESS LAKE
GRAHAM LAKE
NORTH WABASCA LAKE
SOUTH WABASCA LAKE
UTIKUMA LAKE
LESSER SLAVE LAKE
CALLING LAKE
GORDON LAKE
WINEFRED LAKE
LAC LA BICHE
LAKE CLAIRE
MAMAWI LAKE
RICHARDSON LAKE
NAMUR LAKE
STURGEON LAKE
SNIPE LAKE
CARDINAL LAKE
WINAGAMI
FORT CHIPEWYAN AWOS A
FORT CHIPEWYAN A
3072657 - FORT CHIPEWYAN
PRAIRIE RIVER
3063630 - KEANE LO
3062360 - EMBARRAS A
3070701 - BIRCH MOUNTAIN TOWER
3060700 - BIRCH MOUNTAIN LO
3060922 - BUCKTON LO
3065492 - RICHARDSON LO
3063563 - JOHNSON LAKE LO
3073792 - LEGEND LO
3060705 - BITUMONT LO
3062675 - FORT MACKAY RS
3064528 - MILDRED LAKE
3064531 - MILDRED LAKE
3064740 - MUSKEG LO
3075790 - SEAFORTH LO
3071555 - CHIPEWYAN LAKES LO
3066380 - THICKWOOD LO
3062693 - FORT MCMURRAY A
3066160 - STONEY MOUNTAIN LO
3060281 - ANZAC
3060280 - ANZAC
3066155 - STONEY MOUNTAIN
3063930 - LIVOCK LO
3062905 - GRANDE LO
3060756 - BOVINE CREEK AFS
3060110 - ALGAR LO
3061930 - COWPAR LO
3073F4M - KIMIWAN LO
BEAVERLODGE CDA
3072783 - GIFT LAKE LO
3074750 - MUSKWA LO
3076908 - WABASCA RS
3072100 - DOUCETTE LO
3065700 - SALT PRAIRIE LO
3064220 - MARTEN MOUNTAIN LO
3064515 - MERIDIAN LO
3065715 - SANDY LAKE LO
3065705 - SALT PRAIRIE RS
3064300 - MAY LO
3061800 - CONKLIN LO
3062839 - GORDON LAKE LO
HIGH PRAIRIE AGDM
3063162 - HIGH PRAIRIE A
3066920 - WAGNER
3066003 - SLAVE LAKE HQTRS
3065160 - PELICAN MOUNTAIN LO
3061580 - CHRISTINA LO
3067590 - WINEFRED LO
SLAVE LAKE A
3065999 - SLAVE LAKE A
3065515 - ROCK ISLAND LAKE LO
3066935 - WANDERING RIVER RS
3066001 - SLAVE LAKE A
3062630 - FLATTOP LO
3063347 - HOUSE MOUNTAIN LO
3066017 - SMITH
3061117 - CALLING LAKE RS
3063120 - HEART LAKE LO
3076680 - VALLEYVIEW AGDM
3062020 - DEER MOUNTAIN LO
3066018 - SMITH RS
ATMORE AGDM
3060321 - ATHABASCA 2
LAC LA BICHE (AUT)
LAC LA BICHE CLIMATE
3074494 - MEEKWAP
3066297 - SWAN HILLS
3066298 - SWAN HILLS RS
3065693 - SALTEAUX

LEGEND

- CLIMATE STATION
- WATERCOURSE
- ATHABASCA RIVER
- CITY
- HYDROLOGIC REGION
- WATERBODY

75 0 75

SCALE 1:2,000,000 KILOMETRES

REFERENCE

Hydrography and city data obtained from Natural Resources Canada. Road data obtained from DMTI.
Hydrometric stations, hydrologic regions, and sub-basin data obtained from Alberta Environment.
Projection: Alberta 10TM False Easting 500,000 at 115 ° W. Datum: NAD 83

I:\2008\08-1326-0033\Mapping\MXD\RSA\Hydrology\FigC-3_Athabasca_ClimateStations_17x22.mxd

PROJECT

Government of Alberta
Environment

HYDRO-CLIMATE MODELLING OF LOWER ATHABASCA REGION

TITLE

CLIMATE STATIONS IN THE LOWER ATHABASCA REGION

Golder Associates
Calgary, Alberta

PROJECT NO. 08-1326-0033			SCALE AS SHOWN	REV. 0
DESIGN	OK	20 Feb. 2009		
GIS	PT	26 Jun. 2009		
CHECK	AB	05 Aug. 2009		
REVIEW	AB	05 Aug. 2009		

FIGURE: C.3

APPENDIX D

HSPF Model Schematic for the Athabasca River Basin

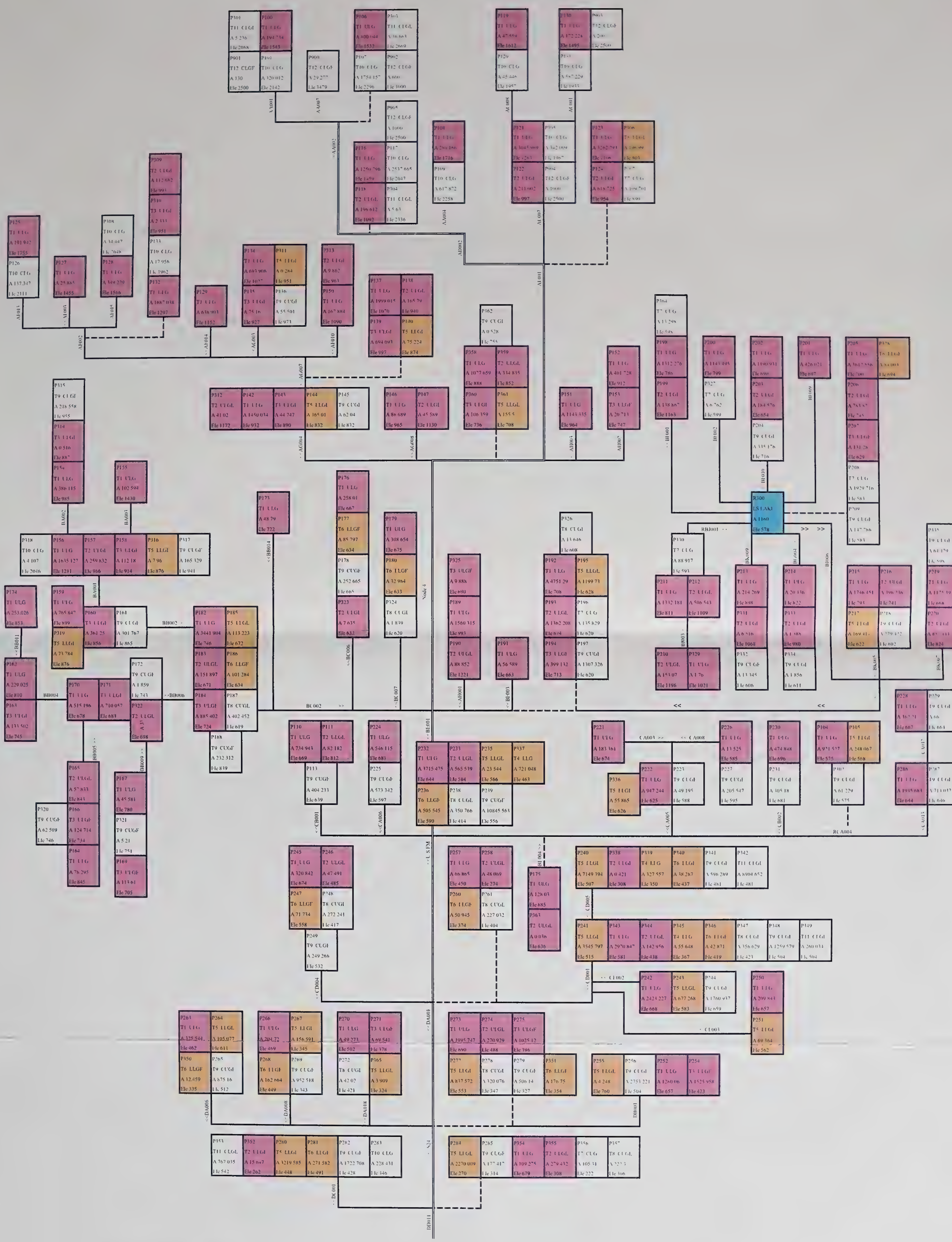

Figure D.1 HSPF Flow Chart for Athabasca River Basin

APPENDIX E

HSPF Model Calibration and Validation Results for Athabasca River Basin and Beaver River Basin

(Provided electronically because of large data sets)

APPENDIX F

Baseline 1961-1990 Average Temperature and Precipitation for Sub-Basins in Athabasca River Basin and the Beaver River Basin

(Provided electronically because of large data sets)

APPENDIX G

Average Changes in Temperature and Precipitation for the 2020s Climate Scenarios for Sub-Basins in the Athabasca River Basin and the Beaver River Basin

(Provided electronically because of large data sets)

APPENDIX H

Average Changes in Temperature and Precipitation for the 2050s Climate Change Scenarios for Sub-Basins in Athabasca River Basin and the Beaver River Basin

(Provided electronically because of large data sets)

APPENDIX I

Comparison of Flow Statistics using the Baseline Climate Data and the 2020s Climate Forecasts

(Provided electronically because of large data sets)

APPENDIX J

Comparison of Flow Statistics using the Baseline Climate Data and the 2050s Climate Forecasts

(Provided electronically because of large data sets)

APPENDIX K

Climate Change and Climate Variability Statistics on the Firebag River Sub-Basin

(Provided electronically because of large data sets)

Golder Associates

At Golder Associates we strive to be the most respected global group of companies specializing in ground engineering and environmental services. Employee owned since our formation in 1960, we have created a unique culture with pride in ownership, resulting in long-term organizational stability. Golder professionals take the time to build an understanding of client needs and of the specific environments in which they operate. We continue to expand our technical capabilities and have experienced steady growth with employees now operating from offices located throughout Africa, Asia, Australasia, Europe, North America and South America.

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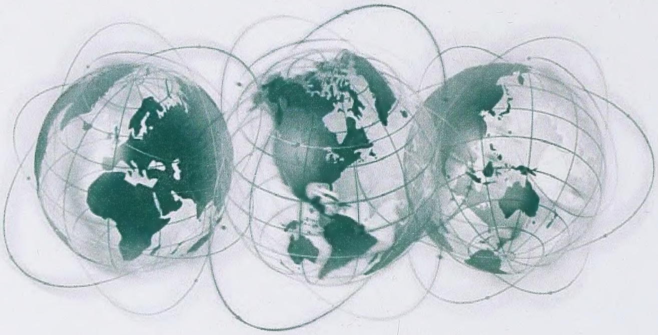

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